

DYNAMICAL AND OBSERVATIONAL CONSTRAINTS ON THE ORIGIN
AND EVOLUTION OF THE SOLAR SYSTEM DUST BANDS

By

KEITH GROGAN

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The title page of this dissertation lists one author, a gesture necessary to satisfy the Graduate School but a rather impertinent gesture nevertheless. I would like to acknowledge the guidance and seemingly limitless patience of my advisor Stanley Dermott and to thank him for making sure my journey through graduate school was an enjoyable one.

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By

Keith Grogan

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The Solar System dust bands discovered by the Infrared Astronomical Satellite (IRAS) are toroidal distributions of dust particles with common proper inclinations. It is impossible for particles with high eccentricity (approximately 0.2 or greater) to maintain a near constant proper inclination as they precess, and therefore the dust bands must be composed of material having a low eccentricity, pointing to an asteroidal origin. The IRAS observations of the zodiacal cloud from which we isolate the dust band profiles have excellent resolution (2 arcminutes) and the manner in which these profiles change around the sky helps to determine the origin of the bands, their radial extent, the size-frequency distribution of the material and the optical properties of the dust itself. The 'equilibrium model', which associates the dust bands with a continual

comminution of material from the major Hirayama asteroid families, suggests Themis and Koronis as the parents of the central band and Eos as the parent of the ten degree band. This dissertation presents evidence from detailed numerical modeling of the bands which strengthens the genetic link between the bands and these families and argues in favor of the equilibrium model. Evidence is also presented suggesting that there are significant dispersions in the orbital inclinations of the Eos material. Investigation of the effects of a random walk in the dispersion of orbital inclinations (a rudimentary treatment of the effect of electromagnetic scattering) suggests that such a mechanism does not produce the Eos dispersion. Evidence is also presented to suggest that the distribution of asteroidal material in the inner solar system is more heavily weighted towards the asteroid belt than expected from a simple Poynting-Robertson drag distribution, implying that particles break up and are blown out of the system. Results of modeling the dust bands including a size-frequency distribution may suggest that a significant large particle component is required in the inner Solar System, consistent with LDEF cratering records. Future work with the COBE data at low elongation angles will further reveal the extent of the three-dimensional structure of the bands and serve to constrain estimates for the asteroidal component of the zodiacal cloud.

CHAPTER 1 INTRODUCTION

Dust in the Solar System

The zodiacal light appears in the night sky as a dim triangular glow, climbing from the horizon into the sky along the ecliptic. This is the optical manifestation of a tenuous cloud of dust which pervades the inner solar system; at 1 AU the concentration of dust particles with radii between 1-1000 μm is a few particles per km^3 , while estimates for the mass of the whole cloud are 10^{16} - 10^{17} kg, approximately the mass of one large comet (Leinert and Grün 1990). The conical shape of the zodiacal light implies a flattened, lenticular shape for the dust cloud and it is the usual practice in the literature to invoke simple models to describe the distribution of this dust in interplanetary space. The radial dependence and out-of-ecliptic dependence of the number density distribution of the dust particles are separated and the dust distribution is approximated by an expression of the form

$$n(r, z) \sim r^{-v} f(\beta) \quad 1.1$$

where z is the height above the ecliptic plane and $\beta = \arcsin(z/r)$ is the heliocentric latitude (Giese et al. 1986). The brightness of the zodiacal light along any given line of sight can then be expressed as the integral of the thermal and scattering emissivities:

$$Z_\nu = \rho \int n(r, z) \left[A_\nu F_\nu \Phi(\Theta) + (1 - A_\nu) E_\nu B_\nu(T) \right] ds \quad 1.2$$

where ρ is the volumetric extinction cross-section at 1 AU, A_ν is the albedo at frequency ν , F_ν is the solar flux at frequency ν , $\Phi(\Theta)$ is the phase function at scattering angle Θ , E_ν is the emissivity at frequency ν , T is the grain temperature and $B_\nu(T)$ is the Planck function.

Structure in the Zodiacal Cloud

The Infrared Astronomical Satellite (IRAS) was launched in 1983, a joint U.S., Dutch and British project to study emission from extragalactic objects, star-forming regions and other regions of interest in the infrared sky. IRAS performed photometry in four wavebands, 4, 12, 25 and 60 microns and the observing strategy was ideally suited to the study of the zodiacal cloud: the telescope line of sight was held at a constant solar elongation angle and swept from pole to pole. Therefore in one satellite orbit two such scans were made, one in the 'trailing' direction (the direction opposite the direction of the Earth's motion about the Sun) and one in the 'leading' direction; near complete sky coverage was achieved in six months. The legacy of this observing program from the point of view of zodiacal light researchers is many thousands of zodiacal cloud brightness profiles. Figure 1-1 shows the zodiacal cloud as seen by IRAS in the four photometric wavebands, each profile is the result of coadding a subset of profiles in ecliptic longitude to reduce noise. Galactic emission is clearly evident at high latitudes in the longer wavelength data and the zodiacal emission peaks

in the 25 micron waveband. However, one of the major surprises of the IRAS mission is evident in these diagrams: the zodiacal cloud is not completely smooth. All four wavelengths show extra emission superimposed onto the smooth zodiacal background, 'shoulders' at roughly $\pm 10^\circ$, and a 'cap' near the ecliptic. In the discovery paper, Low et al. (1984) suggest that these 'dust bands' are traces of collisional debris within the main asteroid belt, based on a determination of their color temperature. This is an important point: the traditional dominant source of the interplanetary dust complex was assumed to be the debris of short period comets (Whipple 1967; Dohnanyi 1976). Although asteroidal collisions should inject at least some material into the cloud, the lack of observational constraints had otherwise made the contribution of asteroidal material next to impossible to estimate.

Sources of Structure in the Zodiacal Cloud

Dust Bands

A dust band is a toroidal distribution of dust particles with common inclinations. The dust particles themselves are asteroidal collisional debris. Particles in cometary type orbits have high orbital eccentricities; planetary gravitational perturbations produce large variations in these eccentricities and these variations are coupled to those in the inclinations (Liou et al. 1995). Therefore even if a group of cometary type orbits initially had identical inclinations, planetary perturbations would disperse those inclinations over a

wide range on a timescale of a few precession periods, showing that it is impossible for a comet to produce a well defined dust band.

A given asteroid undergoing a collision will break up producing debris according to some size-frequency index q . Assuming the excess velocities after escape are small compared with the mean orbital speed of an asteroid (15-20 km/s), the orbits of individual fragments will be similar as their orbital elements will be only slightly perturbed from those of the parent asteroid (Davis et al. 1979). Even a small initial distribution in relative velocity (10-100 m/s), corresponding to a minor distribution in semi-major axis (0.1-1%) rapidly produces a ring of material over the parent asteroid's orbit (10^2 - 10^3 years).

Secular precession acts upon the particles' longitude of ascending node due to the effect of Jovian perturbations. To first order,

$$\langle \dot{\Omega} \rangle = -\frac{3GM_J a^{3/2}}{4R_J^3 \sqrt{GM_S}} \left[1 + \frac{15}{8} \frac{a^2}{R_J^2} \right] \quad 1.3$$

where Ω is the longitude of node, M_J is Jupiter's mass, M_S is the Sun's mass, R_J is the mean orbital distance of Jupiter (5.2 AU), a is the semi-major axis of a given particle and G is the gravitational constant (Sykes and Greenberg 1986). The rate of nodal regression can be found by taking the derivative of Equation 1.3,

$$\Delta \langle \dot{\Omega} \rangle = \frac{9}{8} \frac{GM_J a^{3/2}}{R_J^3 \sqrt{GM_S}} \left[1 + \frac{35}{8} \frac{a^2}{R_J^2} \right] \frac{\Delta a}{a}. \quad 1.4$$

The time taken to distribute the nodes around the ecliptic to form a dust band is then given by

$$\Delta t = \frac{2\pi}{\Delta\langle\dot{\Omega}\rangle}. \quad 1.5$$

For a collisional event at 2.2 AU with ejection velocities of 100 m/s, a dust band would form after approximately 2×10^6 years. Now since particles in inclined orbits spend a disproportionate amount of time at the extremes of their vertical harmonic oscillations, a set of such orbits with randomly distributed nodes will give rise to two apparent bands of particles symmetrically placed above and below the mean plane of the system (Neugebauer et al. 1984). This gives a natural explanation for the 'shoulders' on the IRAS profiles at approximately $\pm 10^\circ$. Similarly, the central 'cap' may be simply explained as a low inclination dust band. Figure 1-2 shows this dust band structure in terms of a slice in ecliptic longitude through a model dust band. The position of each point is found via direct numerical integration. The integrations were stopped at 0.5 AU, hence the central gap.

Earth's Resonant Ring

IRAS observations of the zodiacal cloud revealed a peculiar asymmetry, namely that the peak brightness of the zodiacal cloud in the trailing direction is consistently greater than that in the leading direction (Dermott et al. 1988). This asymmetry is approximately 3-4% for each waveband. Numerical integrations show that a significant fraction of dust particles spiraling into the Sun via Poynting-Robertson (P-R) drag (a phenomenon which follows from the fact that dust particles are irradiated from the solar direction but reradiate isotropically, leading to a loss of angular momentum and a subsequent decrease in semi-major

axis) are trapped in corotational resonances external to the orbits of each of the terrestrial planets, particularly the Earth (Jackson and Zook 1989; Dermott et al. 1994b). The result is that the Earth is embedded in a ring of dust particles that is longitudinally near uniform except for a cavity that contains the planet. The action of drag introduces a phase lag into the equation of motion of these resonant particles, and the physical manifestation of this is a phase difference between the longitude of conjunction of the dust particle and the Earth and the apocenter of the dust particle's orbit. The result is that the position of the Earth within the cavity is markedly asymmetric, with the Earth closer to the edge of the cavity in the trailing orbital direction (Figure 1-3), giving a natural explanation for the trailing/leading asymmetry observed by IRAS.

Interstellar Dust

Impact data from the Ulysses dust detector at 5 AU from the Sun have been interpreted as a flux of submicron interstellar dust particles (Grün et al. 1994). By following the motions of these particles under the influence of solar gravity, radiation pressure and electromagnetic forces (Gustafson and Misconi, 1979; Grün et al. 1994; Gustafson and Lederer 1996), Grogan et al. (1996) derive a model for the thermal emission from the resultant particle cloud. Distributions of the particles are time variable depending on the solar cycle. Figure 1-4 presents results representing a snapshot of the interstellar dust distributions for three representative particle sizes in the year 1990 (corresponding to the time of the COBE observations). Figure 1-5 shows the corresponding Aitoff projections

(similar to the presentation of the Weekly Sky Map form of the COBE data set) of the resultant thermal emission. In terms of an asymmetry in the trailing/leading telescope directions, a peak level of approximately 0.1 MJy/Sr is reached in the 12 micron waveband. This represents 10% of the average brightness asymmetry around the sky. A strong seasonal variation in the predicted interstellar emission trailing/leading asymmetry is the most obvious signature of the interstellar source, and in addition the time variability of the emission will produce different features in the IRAS and COBE data sets and in any subsequent infrared mission. For these reasons, traces of local interstellar thermal emission may well be discovered.

Equilibrium vs. Non-Equilibrium

The basic mechanism of dust band production outlined in the previous section is widely accepted in the literature, but a point of debate is whether the dust bands are equilibrium or non-equilibrium features. In other words, are the dust bands produced by a gradual grinding down of the asteroid family members, or do they represent regions of random, catastrophic disruptions in the asteroid belt?

The equilibrium model, discussed in a series of papers produced from the Florida group (Dermott et al.) from 1984 to the present, first appeared in the literature with the observation that the positions of the dust bands follow the locations of the major Hirayama asteroid families (Dermott et al. 1984). This

would be the natural consequence if the local volume density of dust, produced from continual asteroid erosion, followed the local volume density of asteroids. The catastrophic model follows from a discussion of dust band production rates (assuming the random disruption of a small single asteroid of approximately 15km diameter) and dust band lifetimes (material will be removed by P-R drag). Following this logic, Sykes and Greenberg (1986) conclude that several dust bands should be visible at any given time. This is in agreement with the IRAS observations and represents the main argument for the non-equilibrium model.

This question is an important one to answer, and has implications for the investigation of the long-term evolution of the asteroid belt. If the equilibrium model proves correct, then the dust bands can be used as probes of collisional activity within their corresponding families and ultimately employed to estimate the percentage contribution of asteroidal material to the zodiacal dust complex. If the catastrophic paradigm is correct, then individual dust band features cannot be related to given asteroids in the belt with any confidence, and the question of the asteroidal contribution to the cloud will be much more difficult to unravel.

The object of this dissertation is to determine as accurately as possible the contribution of asteroidal material to the zodiacal cloud via investigation of the structure and evolution of the dust bands. Chapter 2 gives an outline of how the problem has been addressed in the thirteen years since the dust bands were discovered. In order to study the dust bands some method of separating them from the smooth zodiacal background has to be employed; chapter 3 details the

fast Fourier filtering method used here. Chapter 4 details the method for the production of model dust bands using the SIMUL modeling algorithm. Chapter 5 presents the results of detailed modeling of the dust bands using the SIMUL modeling algorithm, and discusses the implications for the asteroidal component of the cloud. Chapter 6 suggests directions for future work.

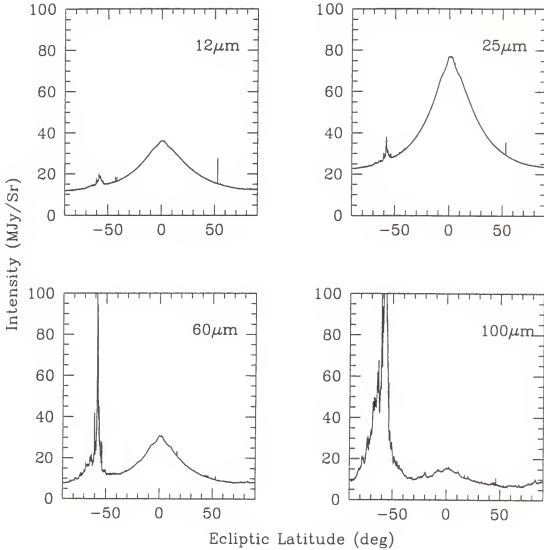


Figure 1-1: A typical IRAS scan showing the brightness profile of the zodiacal cloud in all four wavebands (12, 25, 60 and 100 μm). Here, longitude of Earth is 214.7° and the solar elongation is 90.4° in the leading telescope direction. The cloud is brightest at 25 μm , and the Galactic signal is shown to increase in strength with increasing wavelength.

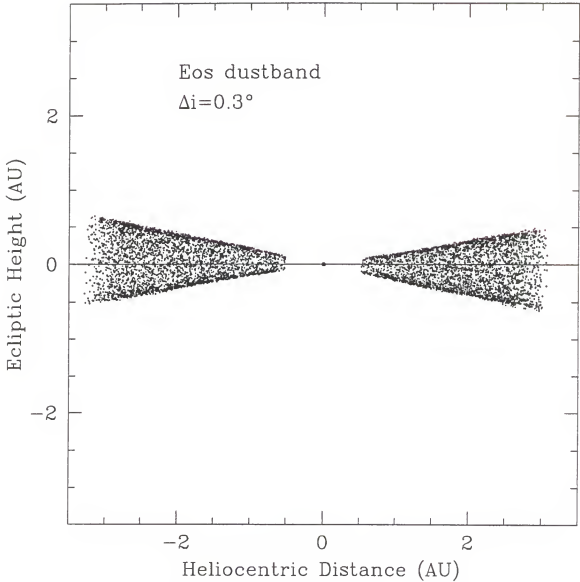


Figure 1-2: The structure of a dust band. The position of each point is obtained via direct numerical integration. The integrations were stopped at 0.5 AU, hence the central gap. The dust band is clearly offset (the left edge is closer to 3 AU than the right edge), and the particles pile up at high latitudes because of a geometrical effect giving rise to the dust bands. The number density of particles within a dust band varies inversely with heliocentric distance. The number density of particles shown in the diagram appears constant with distance, but this is due to the fact that the diagram represents a slice through the cloud in ecliptic longitude and therefore the volume represented increases with heliocentric distance.

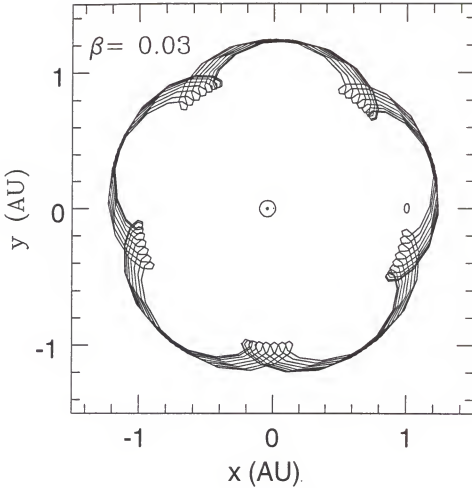


Figure 1-3: Path of a 13 micron diameter ($\beta=0.037$) dust particle trapped in a 5:6 mean motion resonance with the Earth, shown with respect to the frame of reference centered on the Sun and rotating with the Earth's mean motion. In this frame the Earth's orbit is a 2:1 epicycle centered at point (1,0). The orbit is plotted over one complete libration period and the direction of motion of the particle and the Earth are in the anticlockwise direction. The leading and trailing directions of a telescope orbiting the Earth are in the +y and -y direction respectively. Drag forces on the particle introduce a phase shift making the pattern asymmetric about the Sun-Earth line and allowing the orbit to approach closer to the Earth in the trailing direction.

1990

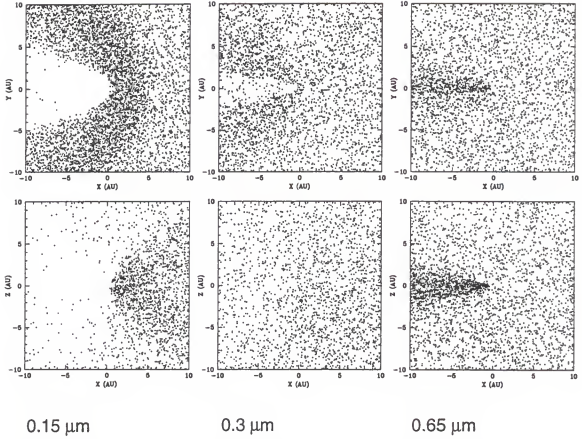


Figure 1-4: Inner solar system distribution of astronomical silicate particles centered on the Sun, calculated for the year 1990 corresponding to the time of the COBE observations. Distributions for 0.15, 0.3 and 0.65 micron radius particles are shown from left to right. The ecliptic plane (XY) distribution is plotted in the upper half of the diagram, and the perpendicular out-of-ecliptic distribution (XZ) is plotted in the lower half. The arrow indicates that in all diagrams the particles enter from the right (upstream, ecliptic longitude 252°) and move toward the left (downstream, ecliptic longitude 72°).

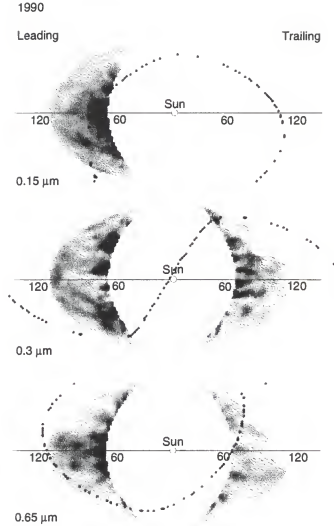


Figure 1-5: Sky maps (Aitoff projections) of the predicted 12 micron wave band thermal emission for 1990 from astronomical silicate particles between 60° and 120° solar elongation angle in both the leading (left) and trailing (right) directions. From top to bottom the maps represent the distributions of 0.15 micron (longitude of Earth 162°), 0.3 micron (longitude of Earth 90°) and 0.65 micron (longitude of Earth 30°) radius particles. The longitude of Earth for each map is chosen such that the trailing/leading asymmetry will be a maximum with the higher intensity in the leading direction. In all diagrams the intensity scale is linear with the darkest areas 0.1 MJy/Sr (0.15 micron particles) 0.06 MJy/Sr (0.3 micron particles) and 0.07 MJy/Sr (0.65 micron particles). The dotted line corresponds to the plane of the Galaxy.

CHAPTER 2

ANALYSIS OF IRAS ZODIACAL DUST BAND OBSERVATIONS

- A LITERATURE REVIEW

Introduction

Since the discovery of the zodiacal dust bands in 1984, several research groups have undertaken an analysis of the bands in order to determine their various properties, such as heliocentric distance, inclination, color temperature and radial extent. Since it is generally accepted that the dust bands originate from the collisional debris of asteroids, implications for the contribution of asteroidal material to the zodiacal cloud as a whole have also been discussed.

Isolating the dust bands

It is impossible to observe the dust bands as discrete features of the zodiacal dust complex. The dust band features have to be isolated from any observation by suppression of the zodiacal background and several distinct methods have been employed in the literature. It could be argued that any technique to isolate the dust bands is potentially as good as any other, as long as the effect of the technique on the ultimate dust band profile is understood and taken into account. Unfortunately, there is little evidence to suggest that this has been achieved.

Box-car Averaging

Sykes (1990) isolates dust band profiles from the IRAS observations by the technique of box-car averaging. This process averages data values over a given filter width (latitude bin) and subtracts that average from the central sample value. The filter is then shifted by one sample and the process repeated. This has the effect of smoothing the data, and the difference between the original data and the smoothed data gives the residuals which are then associated with the dust bands. Sykes reports that a side-effect of this process is that the filtered peak locations are shifted outwards relative to the true peak. Any possible effect on the shape of the bands is not reported. Love and Brownlee (1992) adopt a similar approach in their study of the dust bands.

Fast Fourier filtering

Dermott et al. (1988) use a fast Fourier filter combined with a 'Parzen' window which filters out the low frequency component or the smooth background cloud from the total signal leaving behind the high frequency component, defined to be the dust band profile. The data windowing decreases the leakage from one frequency to another by avoiding substantial components at higher frequencies. The factor that distinguishes between the low and high frequency components is denoted by a constant c which can take values between 0 and 1. Higher values of c increase the fraction of the dust band which is incorporated into the background and it is found that the flux associated with a dust band can vary by a factor of four depending upon the value of c . This serves

to emphasize that the divide between dust band and background is completely arbitrary, since a significant fraction of the dust band is indistinguishable from the background. It is this method, however, which will be applied here, and the method of bypassing the problems associated with the application of the filter are discussed in the next chapter.

Subtracting an empirical background

An alternative approach is to assume some empirical form for the background component, and subtract this from the observations to produce residuals which can then be associated with the dust bands. Reach (1992) decomposes individual IRAS dust band profiles into a fourth order polynomial within 16° of the ecliptic (to represent the smooth background) and four Gaussians, two to represent the ten degree band pair and two for the central band (examination of the dust band residuals reveals a double peak in the central band). It is noted that there are a total of 18 free parameters for each profile; five for the baseline, three each for the four Gaussians, and a coefficient for the HI column density to represent the high-latitude Galactic infrared emission. All $|\beta| < 16^\circ$ scans passing within ten degrees of the Galactic plane are discarded. Two obvious trends reported in the residuals are (1) a sinusoidal annual variation of the band latitudes - due to 'the changing altitude of the Earth with the respect to the midplane of the band pairs' (the dust band material has a forced inclination due to Jovian gravitational perturbations) and (2) a superimposed sawtooth pattern due to elongation angle effects (as the solar

elongation angle increases, dust band material along the line of sight is closer to the telescope, and the apparent latitude of the bands will increase due to a parallax effect).

Jones and Rowan-Robinson (1993) adopt a similar approach, but subtract a modified fan model for the distribution of dust,

$$n_c(r, \beta) = n_0 \left(\frac{r}{1 \text{ AU}} \right)^{-\gamma} f(\beta) \quad 2.4$$

where $f(\beta) = (\cos \beta)^Q \exp(-P \sin |\beta|)$. This is similar to an approach made by Deul and Wolstencroft (1988). The function is smoothed near the ecliptic by a Gaussian to remove 'unwanted peakiness', and a radial cut-off of 1.52 AU is also imposed since the model assumes that the zodiacal cloud is formed by the perturbation of dust in asteroidal bands as it passes close to the orbit of Mars.

Interpreting the dust band profiles

Once the background signal has been removed from the observations, the residual component can then be analyzed. Is it possible to determine the origin of the dust bands from basic properties such as the variation of the amplitude of the dust band profiles and their latitude of peak brightness around the sky? What information, if any, is revealed by the shape of the dust band profiles and their annual variations?

In attempting to address questions such as these, Sykes (1990) takes the approach of comparing the residuals obtained from his box-car averaging

process to empirical models for the dust band profiles. First, he assumes no dispersion in the orbital elements of the dust band material (this assumption may be relaxed later). The volume density of a given dust band torus will then be given by

$$P_{\text{vol}}(r, \beta) = R(r)\Theta(\beta) \quad 2.5$$

$$\text{where } R(r) = \frac{C_r}{a^2 r} \frac{1}{\left[e^2 - (r/a - 1)^2\right]^{1/2}}, \quad \Theta(\beta) = \frac{1}{2\pi^2 [\cos^2 \beta - \cos^2 i]^{1/2}}$$

within the limits $a(1-e) \leq r \leq a(1+e)$, $-i \leq \beta \leq i$. Note that β is the heliocentric latitude with respect to the plane of symmetry of the band. These equations describe a spatial distribution that is a torus with a squarish cross-section, centered on the Sun, whose radial extent is bounded by the perihelion and aphelion distance, and whose latitudinal extent is bounded by the inclination of the particle orbits. Maxima in number density occur at the ‘corners’ of the torus and the latitudes of the maxima as viewed from the Sun correspond to the proper inclination of the particle orbits.

Dispersion in orbital inclination may now be included in the following manner. The outer edge of a band is defined by the location where the peak flux drops by half. The inner edge is defined as the latitude where the flux equals the average of the fluxes at the peak and the midplane. A dispersion δi will act to increase the latitude of the outer edge by an amount Δ_o , and the latitudes of the peak and the inner edge will decrease by an amount Δ_p and Δ_i respectively. The rates of change of these parameters are given (empirically) as

$$\frac{\Delta_+}{i} \approx 0.48 \left(\frac{\delta i}{i} \right)^{0.89}, \quad 2.6$$

$$\frac{\Delta_0}{i} \approx 1.16 \left(\frac{\delta i}{i} \right)^{1.13}, \quad 2.7$$

$$\frac{\Delta_-}{i} \approx 1.73 \left(\frac{\delta i}{i} \right)^{0.84}. \quad 2.8$$

The ratio of peak flux, F_p , to the flux at the midplane, F_c is approximated by

$$\frac{F_p}{F_c} \approx 0.71 \sqrt{\frac{\delta i}{i}}. \quad 2.9$$

It is reported that these four relationships are accurate to within 'a few percent' for $i < 20^\circ$ and $\delta i/i < 0.25$. The statement is made that these inclination dispersion effects serve to (1) broaden the profile (2) shift the peak to a lower latitude. Note that these effects of dispersion on the appearance of dust band profiles had previously been predicted in Dermott et al. (1990).

Secular perturbations are included by the following expressions for the perihelion and aphelion band distances, following Dermott et al. (1984, 1985):

$$r_p = a(1 - e + e_f \cos(\lambda - \varpi_f)) \quad 2.10$$

$$r_a = a(1 + e + e_f \cos(\lambda - \varpi_f)) \quad 2.11$$

where λ is the heliocentric longitude of observation. The heliocentric latitude of the peak and outer and inner edges are given by:

$$\beta_0 = i_f \sin(\lambda - \Omega_f) \pm (i - \Delta_0) \quad 2.12$$

$$\beta_\pm = i_f \sin(\lambda - \Omega_f) \pm (i - \Delta_\pm) \quad 2.13$$

$$\beta_- = i_f \sin(\lambda - \Omega_f) \pm (i - \Delta_-) \quad 2.14$$

In order to compare theoretical dust band models with observations, an algorithm is developed to generate artificial geocentric scenes based on any given parameter values in the above equations. This utilizes the pointing information contained in the IRAS Zodiacal Observational History File (ZOHF) and an ephemeris of the Earth over the period of the IRAS mission. Along the fixed circle of solar elongation for each scan, geocentric positions of perihelion and aphelion bands for an arbitrary dust band torus are calculated, thereby simulating IRAS observations of model dust bands.

Given these models for the distribution of material in the dust bands, Sykes then states the most probable source of each band from matching these models with the filtered profiles. Appropriate forced elements are taken from Dermott et al. (1985) and dispersion is increased until the shapes give a reasonable match. Sykes concludes that the central band is most likely associated with the Themis and Koronis asteroid families at their location in the asteroid belt. The contribution of Koronis dust required is much greater than that of Themis dust. The ten degree band matches best with an Eos family asteroid source with a dispersion in orbital inclination of 1.4° , although this dispersion makes the model bands a little too broad. Maria family model bands consistently fall interior to the observed '17° bands', a problem which cannot be removed by dispersion since dispersion acts to decrease the latitude of peak emission even further. The fact that there is no dust band at approximately 5° (the position of

the Flora family) is taken to be evidence against the equilibrium model: if the equilibrium model is correct, every major family should have an associated dust band.

Reach (1992) follows Sykes (1990) in constructing empirical models for the dust bands and matching them with the observations. A simplified model of the dust bands is considered in which each band pair consists of two parallel rings with radius R , centered on the Sun, separated by a distance $2z$, inclined to the ecliptic by an angle i , with the midplane of intersecting the ecliptic with longitude of ascending node Ω . The rings are assumed circular since the forced eccentricities are taken to be negligible. By geometry, the latitudes of the northern and southern bands are then given by

$$\beta_N = \tan^{-1} \left[\frac{z + R \tan i \sin(\lambda_h - \Omega)}{\cos \varepsilon + \sqrt{R^2 - \sin^2 \varepsilon}} \right] \quad 2.15$$

$$\beta_S = \tan^{-1} \left[\frac{-z + R \tan i \sin(\lambda_h - \Omega)}{\cos \varepsilon + \sqrt{R^2 - \sin^2 \varepsilon}} \right] \quad 2.16$$

where λ_h is the heliocentric longitude at which the line of sight intersects the band, and ε is the solar elongation angle. The average latitude of a band pair is then given by

$$\tan \beta = \frac{\tan \beta_N + \tan \beta_S}{2} = -\frac{R}{\sqrt{R^2 - 1}} \tan i \sin(\lambda - \Omega \pm \sin^{-1}(1/R)) \quad 2.17$$

at $\varepsilon=90^\circ$, where $\pm$ denotes leading/trailing lines of sight. This equation leads to a best-fitting inclination and node for each band pair.

The distance to a given band pair is derived from the variation of the band pair separation of a function of solar elongation angle (parallax). This band pair separation,

$$\Delta \tan \beta = (\tan \beta_N - \tan \beta_S) = \frac{2z}{\cos \varepsilon + \sqrt{R^2 - \sin^2 \varepsilon}} \quad 2.18$$

and near $\varepsilon=90^\circ$ the first order expansion of this is given by

$$\Delta \tan \beta \approx \frac{2z}{\sqrt{R^2 - 1}} \left[1 + \frac{1}{\sqrt{R^2 - 1}} \left(\varepsilon - \frac{\pi}{2} \right) \right]. \quad 2.19$$

This expression can then be used to obtain R for a given band pair at a given heliocentric longitude.

A problem arises when the distances to the band pairs are calculated as a function of heliocentric longitude. It is found that the distances to both central and ten degree band pairs when estimated using this technique vary from 1.3 AU to 2.7 AU. Reach proposes that a possible explanation for this is the existence of significant radial and azimuthal asymmetry in the distribution of interplanetary dust. Reach also plots the distance data (as a function of heliocentric longitude) in polar coordinates with the purpose of giving some idea of the shape of the band. For example, any ellipticity in the shape of a dust band would be a direct measure of the forced eccentricity of the dust particle orbits. However, there is a large amount of scatter in the plot, and Reach suggests that this serves to place an upper limit on the forced eccentricity of the dust of around 0.3. It is also noted that since the inclination of the outer band pair is smaller than Eos, this indicates

that this band is probably not associated with a family but with debris of an asteroid having a inclination smaller than that of Eos.

Reach calculates the 12/25 and 60/25 colors from the tabulated peak brightnesses and uses these to give the temperatures of the central and ten degree bands assuming that the dust particles radiate as blackbodies. This then gives another measure of the distance of the bands. The outer band temperature is found to be 180K (distance 2.3 AU) and the central band temperature is found to be 209K (distance 1.8 AU). Since these temperatures are warmer than expected if the material was simply distributed at the location of the families in the asteroid belt, Reach takes these results as evidence that the dust band material has migrated inwards via Poynting-Robertson drag. The collisional debris is now separated into two evolutionary classes: (1) large fragments, unaffected by radiation pressure which stay in the asteroid belt, (2) small fragments migrating towards the Sun via P-R drag. Now, the integrated brightness along the line of sight,

$$I_v(\beta) = \int ds E_v(r, \beta_h) \quad 2.20$$

where E_v is the volume emissivity, r is the heliocentric distance, β_h is the heliocentric latitude and β is the geocentric latitude. An actual expression of the number density of particles in the band can be found in Reach et al. (1996),

$$n_{B_i}(r, \zeta_{B_i}) = n_{1B_i} R^{-1} \exp \left[- \left(\zeta_{B_i} / \delta \rho_{B_i} \right)^6 \right] \left[v_{B_i} + \left(\zeta_{B_i} / \delta \rho_{B_i} \right)^{p_{B_i}} \right] \quad 2.21$$

where n_{1bi} is the density at 1 AU relative to that of the smooth cloud of band i , $\zeta_{bi} = z_{bi}/R$, z_{bi} is the vertical distance from the midplane of band i , and δ_{pbi} , v_{bi} and p_{bi} are adjustable shape parameters. Note the $1/R$ dependence to account for the expected P-R drag distribution.

Using these empirical models to fit the residuals, Reach reports the best fit for the outer band pair is given with $i=8.5^\circ$, $R=2.7\text{AU}$ and a dispersion in orbital inclination of 0.4° . Dispersion is not included in any of his model expressions so it is unclear how dispersion is factored into the analysis. He is unable to fit the central band at all, citing problems with his polynomial fitting routine to the IRAS profiles which are most extreme near the ecliptic.

Jones and Rowan-Robinson (1993) also take an empirical approach in modeling the dust bands,

$$n_b = n_0 A_b (r/r_b)^{-\alpha} f_b(\beta) \quad 2.22$$

for $1.52\text{AU} < r < r_b$ ($=0$ otherwise) where A_b is a band normalization, r_b is the outer cut-off, $\alpha=1$ (P-R drag) and

$$f_b(\beta) = \exp(G(\beta_b - \beta)) \quad 2.23$$

for $\beta < \beta_b$ ($=0$ otherwise) where β_b is the maximum extent of the bands above the symmetry plane. A problem is raised however when these expressions fail to adequately model the ten degree band. This band is broad and the models do not account for a dispersion in inclination. Therefore a separate 'broad-band component' is introduced:

$$n_{bb}(r, \beta) = n_0 A_{bb} (r/r_{bb})^{-1} f_{bb}(\beta) \quad 2.24$$

for $1.52 \text{ AU} < r < r_{bb}$ ($=0$ otherwise) where the latitudinal profile is given by a double-Gaussian:

$$f_{bb}(\beta) = \left\{ \exp\left[-\frac{(\beta - \beta_{bb})^2}{2\sigma_{bb}^2}\right] + \exp\left[-\frac{(\beta + \beta_{bb})^2}{2\sigma_{bb}^2}\right] \right\} \quad 2.25$$

where β_{bb} is the latitude of the peaks above the symmetry plane and σ_{bb} is the peak width. In comparing the model with observations, the IRAS fluxes are first corrected for the assumed incident spectrum - emission from a blackbody at 255K since the bulk of the emission occurs near 1AU. (Data at less than galactic latitude 30° are excluded.) Then the models are compared to the residuals (fan model subtracted from the observations). The reported best fit for the 'broad-band component' (the ten degree band) is a distance of 3 AU, which differs from an earlier estimate by Rowan-Robinson et al. (1991) of 50 AU based on color temperature analysis of IRAS sky maps after the subtraction of a primitive fan model for the background.

Love and Brownlee (1992) attempt to determine the fraction of dust band material to the total zodiacal cloud. They attempt to do this using 60 and 100 micron data, since long wavelengths will preferentially pick up cooler emission from the asteroid belt. They claim that these wavebands will also better sample the size distribution of dust collected at the Earth (> 30 micron diameter as opposed to smaller material). The analysis is performed in the following manner: take an IRAS profile, transform it from geocentric to heliocentric coordinates to

compensate for different viewing geometries from profile to profile, and then filter by means of box-car smoothing (a similar approach to Sykes 1990). The residuals are identified as the total extent of dust band material, leading to estimates of 0.1% and 0.2% of the total zodiacal dust complex lying in the central and ten degree bands respectively. These estimates are claimed to be lower limits since (1) the extent of the underlying emission from the Galaxy is unknown, and (2) the underlying emission may be over-represented by foreground emission. The estimates are therefore increased by a factor of 5 to 0.5% and 1.0%.

Inadequacies of previous dust band analysis

There is a fundamental flaw in all of the techniques described above. The following question is neither asked nor addressed: How do the dust band residuals depend on the technique employed? For example, in subtracting a fourth order polynomial to suppress the background, Reach (1992) makes no comment on how the residuals may be affected by subtracting, for example, a fifth order polynomial instead. Color temperature analysis depends upon the amplitudes of the dust bands in different wavelengths. To what extent is it certain that employing different techniques will produce stable results? What would a dust band look like if it were viewed as a discrete feature? How do filtered residuals from analyses such as these differ from the 'perfect' dust band? None of these points are answered to any extent, let alone satisfactorily.

A Physical Model for the Solar System Dust Bands

The legacy of the IRAS, COBE and ULYSSES spacecraft is a realization that the zodiacal cloud may consist of five distinct and significant components. These are (1) the asteroidal dust bands, (2) dust associated with other background asteroids, (3) dust associated with cometary debris, (4) the Earth's resonant ring, and (5) interstellar dust. The approach of the Florida group (Dermott et al.) has been to place constraints on the origin and evolution of material of a given source from both dynamical considerations and observational data. Given a postulated source of particles, the aim is to describe (1) the orbital evolution of these particles, including P-R drag, using equations of motion that include the solar wind, light pressure and planetary gravitational perturbations, and (2) the thermal and optical properties of the particles and their variation with particle size. Once the dust particles and their distribution have been specified along these lines, a line-of-sight integrator is employed to not only view the model cloud but to reproduce the exact viewing geometry of any particular telescope in any given waveband. The result is a series of model profiles which can then be compared with observations. It is this approach that will be applied to the dust bands in this dissertation.

The SIMUL Model

Dermott et al. (1984) were the first to suggest that the Solar System dust bands may originate in the three prominent Hirayama asteroid families (Eos, Themis and Koronis). To confirm their hypothesis of the asteroidal origin of the

dust bands, and to facilitate the investigation of the zodiacal cloud in general, Dermott et al. constructed a three-dimensional numerical model, SIMUL. This model is discussed at length in Chapter 4. However, the basic ideas and assumptions of SIMUL are as follows.

- (1) A cloud is represented by a large number of dust particle orbits. The total cross-sectional area of the cloud is divided equally among all the orbits.
- (2) The orbital elements of the dust particle orbits in the cloud can be decomposed into proper and forced vectorial components. When inclination and eccentricity are low, as is typically the case for asteroidal type orbits, the forced elements are independent of the proper elements and depend only on the semi-major axis and the particle size.
- (3) The dust particles in the cloud produced by asteroid families have the same mean proper elements as those of the parent bodies, although the Gaussian distribution of these elements is a free parameter.
- (4) The forced elements as a function of semi-major axis are calculated using secular perturbation theory via direct numerical integrations (Dermott et al. 1992).
- (5) Along each of the orbits, particles are distributed according to Kepler's Law. Once the spatial distribution of the orbits is specified, space is divided into a sufficiently large number of ordered cells and then every orbit is investigated for all the possible cross-sectional area contributions to each of the space cells.

The model generates a large three-dimensional array which serves to describe the spatial distribution of the effective cross-sectional area.

- (6) The viewing geometry of any telescope can be reproduced exactly by calculating the Sun-Earth distance and ecliptic longitude of Earth at the observing time and setting up appropriate coordinate systems. In this way, IRAS-type brightness profiles can be created and compared with the observed profiles.

In order to compare the results of the SIMUL modeling algorithm with the IRAS observations, the filtering problem - the fact that a substantial percentage of the dust band signal is indistinguishable from the background - must be addressed. An iterative process (Dermott et al. 1994a) used to estimate the low-frequency component of the dust band and therefore bypass the filtering problem is used here and discussed in detail in the next chapter. This technique alone has the capability of estimating the strength of the underlying dust band signal, not just the small fraction visible above the background cloud. The method has been used to provide further evidence that the central band originates in the Themis and Koronis families (Dermott et al. 1994a), but the origin of the ten degree band has remained elusive. Although Eos is the natural candidate to produce the ten degree band (it has the largest volume and roughly the correct inclination), model Eos profiles consistently fail to match the observed ten degree profiles in both shape and latitude of peak.

Although the iterative filtering process appears successful in accounting for the underlying dust band signal in the background, the effect of the filter on the dust band profiles has to be examined. For example, does the application of the filter change the shape of the 'true' dust band profile? Does the latitude of peak intensity shift to any extent? These questions need to be addressed before any conclusions can be drawn from the comparison of the observed and model profiles. This is the subject of the next chapter.

CHAPTER 3

THE FAST FOURIER FILTER - APPLICATION AND LIMITATIONS

Basic Fourier Transform Theory

The Fourier transform is an efficient computational tool for accomplishing various common manipulations of data. Applications over the past couple of decades have ranged from the assessment of heart valve damage (biomedical engineering) to the suppression of aircraft wing-flutter (applied dynamics) to speech scrambler systems (communications). The basic theory has recently been outlined in Press et al. (1992). The subject of this chapter is the power of the Fourier transform as a low pass filter for the purposes of signal processing.

A physical process may be described either in the time domain, by the values of some quantity h as a function of time t , $h(t)$, or else in the frequency domain where the process is given by its amplitude H (typically complex indicating phase also) as a function of frequency f , $H(f)$, with $-\infty < f < \infty$. Both $h(t)$ and $H(f)$ can be thought of as representations of the same function. The two are related by the expressions

$$H(f) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f t} dt \quad 3.1$$

$$h(t) = \int_{-\infty}^{\infty} H(f) e^{-2\pi i f t} df . \quad 3.2$$

If t is measured in seconds, then f in the above equations is in cycles per second, although other units are equally valid: if h is a function of position x (meters) then H will be a function of inverse wavelength (cycles per meter) and so on.

In practice the complete function $h(t)$ is unknown and is instead sampled at discrete intervals. Suppose that there are N consecutive sampled values, and let Δ denote the time interval between consecutive samples. Therefore,

$$h_k \equiv h(t_k), \quad t_k \equiv k\Delta, \quad k = 0, 1, 2, \dots, N-1. \quad 3.3$$

Further assume (for simplicity) that N is even. With N numbers of input, no more than N numbers of output will be generated; let estimates be sought only at the discrete values

$$f_n \equiv \frac{n}{N\Delta}, \quad n = -\frac{N}{2}, \dots, \frac{N}{2}. \quad 3.4$$

The integral in Equation 3.1 may now be approximated by a discrete sum:

$$H(f_n) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f_n t} dt \approx \sum_{k=0}^{N-1} h_k e^{2\pi i f_n t_k} \Delta = \Delta \sum_{k=0}^{N-1} h_k e^{2\pi i k n / N}. \quad 3.5$$

The final summation in Equation 3.5 is called the discrete Fourier transform (DFT) of the N points h_k . Denote this by H_n ,

$$H_n = \sum_{k=0}^{N-1} h_k e^{2\pi i k n / N}. \quad 3.6$$

Note that the DFT does not depend on any dimensional parameter, such as the time scale Δ . The formula for the discrete inverse Fourier transform (DIFT), which recovers the set of h_k 's exactly from the H_n 's is:

$$h_k = \frac{1}{N} \sum_{n=0}^{N-1} H_n e^{-2\pi i k n / N} . \quad 3.7$$

The Fast Fourier Transform (FFT)

The fast Fourier transform (FFT) is simply an algorithm which speeds computation of the DFT. In writing Equation 3.6 in the form

$$H_n = \sum_{k=0}^{N-1} W^{nk} h_k \quad 3.8$$

it can be seen that the vector of h_k 's is multiplied by a matrix whose (n,k) th element is the constant W to the power $n \times k$, a matrix multiplication which evidently requires N^2 complex multiplications, plus a smaller number of operations to generate the required powers of W . However, by judicious factorization of the DFT before computation (Brigham 1974), the FFT algorithm reduces this N^2 operation to an $N \log_2 N$ process, representing a considerable advantage.

The DFT produces an approximation of the continuous Fourier transform (CFT) in the case where the complete time function $h(t)$ is unknown. The accuracy of the DFT (and therefore the FFT) is a function of the waveform being analyzed. Ideally, the set of non-zero sampled values h_k will represent exactly one period of the original waveform $h(t)$ - the DFT and CFT are exactly equivalent, within a scaling constant, only when this condition is met. If the values h_k do not represent one period of $h(t)$ then the DFT and the CFT differ considerably. Truncation of $h(t)$ at other than a multiple of the period results in the creation of a periodic function with sharp discontinuities. Consequently the

frequency function is no longer a single impulse but rather a continuous function of frequency with a local maximum centered at the original impulse and a series of other peaks called sidelobes. This effect is known as leakage and can be reduced by the process of data windowing.

Data Windowing

Sampling of the function $h(t)$ over a given range may be thought of as multiplying an infinite run of sampled data by a window function in time, one that is zero except during the sampling time $N\Delta$, and is unity during that time. This is the so-called rectangular window, the cause of the leakage problem. It is usual practice to employ a window function that changes more gradually from zero to a maximum and then back to zero over the sampling time in order to minimize leakage; the Fourier transform of a window function of this nature has sidelobe characteristics smaller in magnitude than that of the Fourier transform of the rectangular window. The principal trade-off is between making the central peak as narrow as possible versus making the tails of the frequency distribution fall off as rapidly as possible. The Parzen window represents a good choice.

Application of the FFT to the IRAS observations

The IRAS data consist of a series of intensity profiles, recording the variation of the zodiacal cloud brightness as a function of ecliptic latitude for a given longitude of Earth and solar elongation angle. This signal contains both a low-frequency component, the zodiacal background, and a high-frequency

component that will be associated with the dust bands. The approach is to take the data, apply the FFT (along with a suitable window function), multiply the FFT output by a filter function to isolate the high-frequency component, and finally apply an inverse FFT to produce a filtered data set.

A single IRAS profile obviously does not represent one period of a periodic function, so a Parzen window is applied in the filtering process to reduce leakage. The FFT will be sampled at an equal number of points as the number of data points in our profile; the frequency cut-off is defined by a simple coefficient, c , a number which varies between 0 and 1 to represent the fraction of frequency points to remain after the high frequencies are stripped from the FFT. In other words, defining this coefficient equal to 1 will leave the complete FFT intact. Figure 3-1 demonstrates how more and more of the original profile is incorporated into the low frequency background as the constant c increases. This is a dramatic illustration of the arbitrary nature of any filtering process and the danger of assuming the resultant residuals to represent the complete dust band structure. Any filter employed will be a mechanism to separate arbitrarily between high and low frequencies. How will the extent of the true dust band ever be revealed? This problem is left unaddressed in the literature, a serious drawback since the nature of all sorts of characteristics of the dust band are drawn from study of dust band residuals, which will represent only a small fraction of the total signal. The problem can however be solved by use of the following iterative filtering scheme, illustrated in Figure 3-2.

Figure 3-2a shows a raw model dust band having the same viewing geometry as an observed background (3-2b). In the first iteration 3-2a is added to 3-2b and the resultant sum is filtered to obtain 3-3c, a model dust band (smooth curve); the observed dust bands (noisy curve) are also plotted for comparison. The background obtained from this iteration, shown in 3-2d, is of a higher intensity than the original background due to the fact that it contains two low frequency dust band components, one from the addition of the model dust band and one from the actual dust band in the original observed background (the high frequency component of which was removed in the creation of the observed background). In the final iteration we subtract the excess intensity shown in 3-2d from the original background 3-2b and add 3-2a before filtering to obtain the final dust band 3-2e and the final background 3-2f that agree with the observations. Thus, by using the same filter in the modeling process that we use to define the observed dust bands, and iterating, we are able to bypass the arbitrary divide associated with the filter.

Side effects of the filtering process

What effects, if any, does the application of the filter have on the appearance of the dust band profiles? The amplitude of the filtered profiles will always be less than the 'true' profiles since some of the dust band signal will be lost in the filtered low-frequency background. More subtle effects can be investigated and revealed by modeling. SIMUL is used to create model dust

band profiles, and these can be subsequently compared to the observed profiles using the iterative filtering procedure outlined earlier.

The most obvious side-effect of the filter is to increase the peak latitude of the dust band profile. This is clearly illustrated in Figure 3-3. The solid curves represent the peak north and south latitudes of raw model dust band profiles produced by SIMUL as a function of ecliptic longitude of Earth at a constant solar elongation angle of 90° in the leading direction. Also shown are the peak north and south latitudes of the dust band profiles after applying the iterative filtering procedure (dotted curves). A shift outwards of a degree or two is observed all around the sky. This phenomenon is to be expected since the amplitude of the subtracted background varies with ecliptic latitude - more flux is subtracted near the ecliptic than at higher latitudes. This acts to shift the peak latitude out from the ecliptic. However, as long as the same filter is consistently applied to both observed and model profiles this effect will act equivalently for both and need not be taken into account when attempting to compare the two.

A more subtle effect of the filter arises in attempting the study of one dust band pair alone. For example, in the study of the ten degree band why not simply apply the filter to a model ten degree band and background, and leave out the central band altogether? Figures 3-4 and 3-5 show the results of such an approach. For clarity the various components of any model or observation, namely the background, the central band and the ten degree band pair have each been approximated by a simple function, shown in Figure 3-4. The background is

represented by a quadratic, the central band by a Gaussian, and the ten degree band by a fourth order polynomial. Any combination of these may now be filtered and the results studied - the sum of all three components is shown in the lower right. Results of the filtering process are shown in Figure 3-5. The upper left diagram shows the results of the iterative filtering process on all three components - strong residuals representing both central and ten degree band pairs. However, spurious and perhaps unexpected results are obtained when the central band is omitted. The upper right diagram shows the results of the first application of the filter, in other words before iteration. Strong ten degree residuals are observed as expected. However, after iteration a central band residual appears seemingly from nowhere, as shown on the lower left diagram. The source of this residual can be explained in the lower right diagram which shows the difference between the backgrounds filtered from all components (solid line) and from a background filtered when the central band component was omitted (dotted line). This shows how the filter 'sees' a different shaped background in the two cases, and the difference between the two shows up as the excess near the ecliptic seen in the central right diagram after iteration. Therefore in order to ensure that the filter acts as consistently as possible, all components should be included in the modeling procedure, even when results concerning the nature of only one band are required.

In summary, the nature of the FFT filter and its application to the IRAS observations for study of the dust bands is well understood. Confidence in the

interpretation of the results stems from the fact that the problem of the arbitrary nature of the filter has been solved by the iterative filtering process. Without this technique the FFT method would have the same drawbacks as any other filtering scheme such as box-car averaging - the low-frequency component of the dust bands would be forever lost in the background signal. In addition all details of the filter itself, such as the frequency cut-off, data windowing technique employed and even any possible effects of the filter on the shape of the dust band are moot points - as long as the same filter is consistently applied to both the model and the observations, the results may be confidently compared. The method of producing these dust band models is detailed in the next chapter.

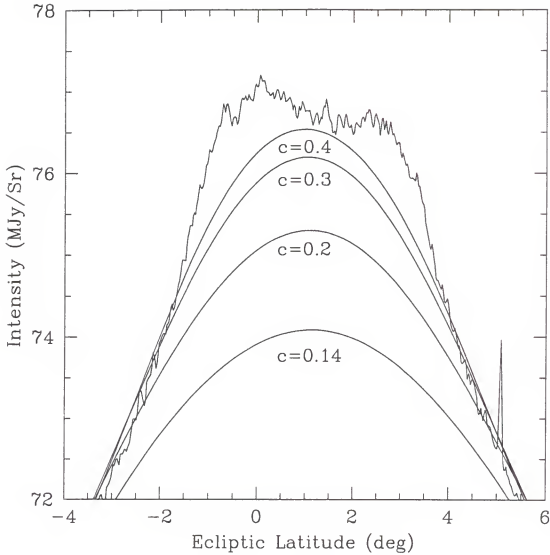


Figure 3-1: The coefficient c represents the fraction of frequency points to remain after the high frequencies are stripped from the fast Fourier transform. This figure shows how more and more of the original profile is incorporated into the low frequency background as the constant c increases. This is a dramatic illustration of the arbitrary nature of any filtering process and the danger of assuming the resultant residuals to represent the complete dust band structure.

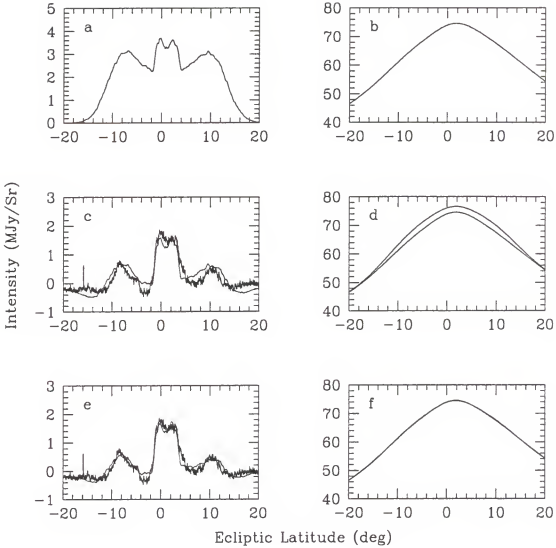


Figure 3-2: The iterative filtering procedure. Figure 3-2a shows a raw model dust band having the same viewing geometry as an observed background (3-2b). In the first iteration 3-2a is added to 3-2b and the resultant sum is filtered to obtain 3-3c, a model dust band (smooth curve); the observed dust bands (noisy curve) are also plotted for comparison. The background obtained from this iteration, shown in 3-2d, is of a higher intensity than the original background due to the fact that it contains two low frequency dust band components, one from the addition of the model dust band and one from the actual dust band in the original observed background (the high frequency component of which was removed in the creation of the observed background). In the final iteration we subtract the excess intensity shown in 3-2d from the original background 3-2b and add 3-2a before filtering to obtain the final dust band 3-2e and the final background 3-2f that agree with the observations.

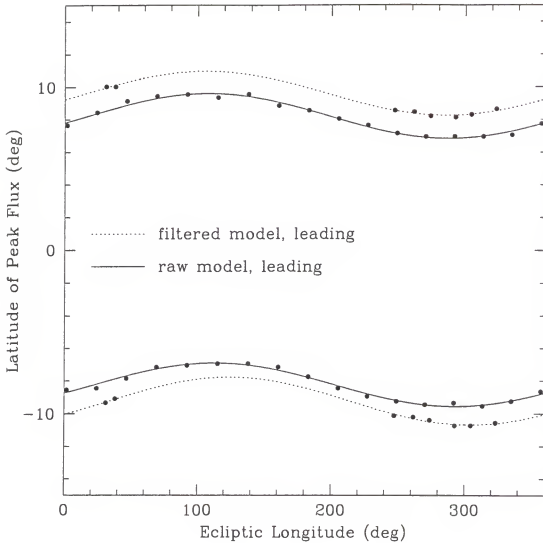


Figure 3-3: One side-effect of the filtering process is to increase the latitude of peak intensity of the dust band profiles. The solid curves show the positions of peak latitude as a function of ecliptic longitude of Earth in the leading direction, solar elongation 90° , for a raw model of the 10° bands. After filtering, these positions have moved out from the ecliptic, shown by the dotted curve. This is to be expected since the amplitude of the subtracted background varies with ecliptic latitude and more flux is subtracted near the ecliptic than at high latitudes. There are less data on the filtered curve because the iterative filtering process requires an observed background at a given longitude of Earth; there are only eight of these observed backgrounds for the leading telescope direction.

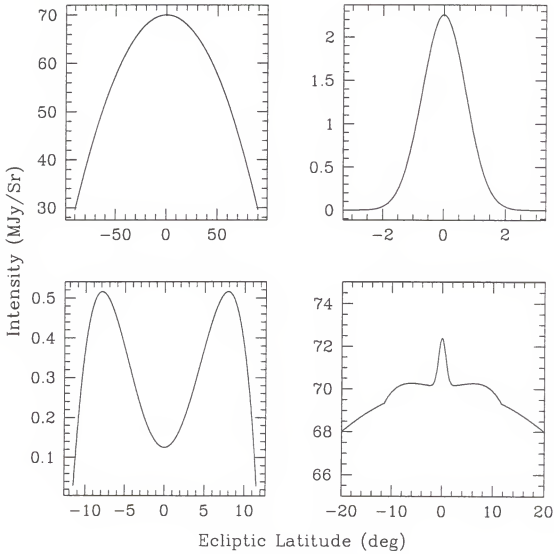


Figure 3-4: The components of a 'perfect' test model for the zodiacal cloud. Upper left: the background is represented by a quadratic. Upper right: the central band is represented by a Gaussian. Lower left: the 10° band is represented by a fourth order polynomial. Lower right: the sum of all three components.

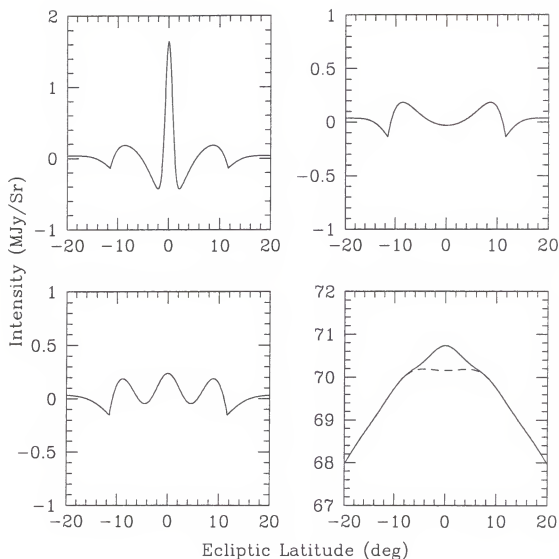


Figure 3-5: A demonstration of the danger of attempting to model one band at a time. Upper left: if all three components from Figure 3-4 are filtered, then strong residuals representing the central and 10° bands are produced. Upper right: filtering the 10° band component alone (first iteration) produces strong residuals as expected. Lower left: after the second iteration a central band residual has appeared, apparently from nowhere. Lower right: the source of this spurious central band. The solid line shows the shape of the background the filter 'saw' when all components were present, while the dotted line is the shape of the background when only the 10° band was included. The difference between the two shows up as the excess near the ecliptic after iteration. For consistent application of the filter, all components of the cloud must be included, even if only one band is being studied.

CHAPTER 4 PRODUCTION OF A MODEL DUST BAND

Dynamical Evolution of Dust Particle Orbits

In order to construct a meaningful model dust band, it is necessary to understand and take into account the various forces acting upon the constituent dust particles. The most obvious is solar gravity,

$$F_{grav}(r) = G \frac{Mm}{r^2} \quad 4.1$$

where G is the gravitational constant and M is the solar mass. Scattering and absorption of solar radiation by a dust particle involve the transfer of momentum and hence to a radiation pressure directed radially outward (Burns, Lamy and Soter, 1979). For spherical particles radiation pressure takes the value

$$F_{rad} = \frac{SA}{c} Q_{pr} \quad 4.2$$

where $S = L/4\pi r^2$ is the radiation flux density at distance r , L is the solar luminosity and Q_{pr} is an efficiency factor averaged over the solar spectrum which can be calculated using Mie theory (see below). Radiation pressure is usually expressed as the ratio of its strength to the gravitational attraction, which for spherical particles is given by

$$\beta = \frac{F_{rad}}{F_{grav}} = 5.7 \times 10^{-5} \frac{Q_{pr}}{\rho s} \quad 4.3$$

where s is the particle radius and ρ and s are given in cgs units. Roughly speaking, radiation pressure balances gravity for a $1 \mu\text{m}$ radius particle.

Interplanetary dust is illuminated anisotropically (from the direction of the Sun) but re-emits the absorbed radiation isotropically. A loss of angular momentum results, and the particle spirals slowly in towards the Sun. This phenomenon is known as Poynting-Robertson (P-R) drag. Owing to aberration, an imaginary observer on the particle would see the incident solar radiation displaced by an angle v_{tan}/c from the radial direction, where v_{tan} is the tangential component of the orbital velocity. From outside, the particle motion causes scattering and thermal emission to have a forward component; the result is a braking force, directed opposite to the direction of orbital motion, equal in first order to v/c times the radiation pressure force for a particle in a circular orbit. Subsequent changes in the orbital elements of the particle are given by

$$\frac{da}{dt} = -\alpha \frac{2 + 3e^2}{a(1 - e^2)^{3/2}} \quad 4.4$$

$$\frac{de}{dt} = -\frac{5\alpha e}{2a^2(1 - e^2)^{1/2}} \quad 4.5$$

$$\frac{di}{dt} = 0 \quad 4.6$$

where

$$\alpha = \frac{3.35 \times 10^{-10} Q_{pr}}{s(m)} AU^2 / yr \quad 4.7$$

Wyatt and Whipple 1950). The consequence is that the orbit shrinks and circularizes, and a particle in a circular orbit at heliocentric distance r spirals into the Sun in a time $\tau_{pr} = 700 s(\mu m) \rho(g/cm^3) r^2(AU) / \langle Q_{pr} \rangle$ years. This equates to several 10^4 years for a 'typical' particle ($10 \mu m$, $2.5 g/cm^3$, $2AU$). Notice that to first order of e ,

$$\frac{da}{dt} = -\frac{2\alpha}{a} \quad 4.8$$

and hence a distribution in semi-major axis

$$f(a) \sim \frac{1}{a}. \quad 4.9$$

Assuming that each orbit in the cloud is comprised of the same number of asteroidal type ($e \approx 0$) particles, it follows that the distribution in particle number density is given by

$$n(r) \sim \frac{1}{r} \quad 4.10$$

where r is the heliocentric distance.

Now consider the motion of dust particles under the effects of planetary gravitational perturbations. When the eccentricity and inclination are small, the solutions of the Lagrangian equations of motion for the eccentricity and pericenter variations may be completely decoupled from the inclination and node variations. These pairs of elements have simple vectorial representations

and may be decomposed into components known as the proper elements and the forced elements of the orbit. The proper elements represent the stable long-term averages that remain after removal of planetary perturbations. The variations due to these perturbations are the forced elements, which can themselves be separated into three categories: (1) secular (long period) perturbations; (2) resonant (short period) perturbations; (3) transient (scattering) perturbations. These perturbations acting on a small body in orbit about the Sun precess the node and pericenter and over sufficiently long intervals the distributions of these elements become essentially random. Figure 4-1 shows a schematic of the vectorial relationship between the total (osculating) elements (i, e, Ω, ϖ), the proper elements ($i_p, e_p, \Omega_p, \varpi_p$) and the forced elements ($i_f, e_f, \Omega_f, \varpi_f$) in both ($e \cos \varpi, e \sin \varpi$) and ($i \cos \Omega, i \sin \Omega$) space. The distributions are displaced from the origin due to the forced elements and the radius of the distributions represents the proper elements.

Building the Model

Selection of orbital elements

The initial proper elements of the dust associated with a dust band are assumed to be given simply by the mean elements and Gaussian dispersions of the associated asteroid family members. These values for the Themis, Koronis and Eos families are given in Table 4-1. To generate semi-major axes between some $a_{\min}$ and $a_{\max}$ (taken to be the location of the source material) according to

some probability distribution $f(a) \sim a^{-n}$, a uniform random x is chosen and then values of semi-major axis may be generated by the following:

$$a = \begin{cases} a_{\max} + x.(a_{\max} - a_{\min}) & n = 0 \\ (a_{\min})^{1-x} (a_{\max})^x & n = 1 \\ a_{\min} \cdot a_{\max} \cdot [a_{\max} - x.(a_{\max} - a_{\min})]^{-1} & n = 2 \end{cases} \quad 4.11$$

Note that $n=1$ corresponds to the P-R drag case. Once a semi-major axis is chosen, the change in eccentricity due to P-R drag can be found from combining Equations 4-4 and 4-5 (Dermott et al. 1994b):

$$\frac{de_p}{da} = \frac{5e_p(1-e_p^2)}{2a(2+3e_p^2)}. \quad 4.12$$

Notice that this variation in eccentricity with semi-major axis is independent of particle size. Equation 4-6 dictates that the proper inclination of a particle does not vary with semi-major axis. Proper nodes and pericenters are assigned randomly.

Once the proper elements have been selected, the forced elements are added vectorially to produce the final osculating elements. The forced elements are the perturbations produced by interaction with the planets, and as such the forced elements will vary not only with heliocentric distance but also with time. These elements are found numerically by direct integration of the full equations of motion of sets of 249 dust particles using the RADAU fifteenth-order integrator code with variable time steps taken at Gauss-Radau spacing (Everhart 1985). All planets except Mercury and Pluto are included. The objective is to calculate each of the forced elements ($i_p, e_p, \Omega_p, \varpi_p$) across the full range of

heliocentric distance (from the source family inwards to the Sun) for a specific time. For this purpose, multiple sets or waves of particles are integrated forwards in time, each having a different starting date, such that they reach different heliocentric distances covering the required range at the year 1983, the year of the IRAS observations to which the model dust bands will eventually be compared. Figure 4-2 shows the evolution of such a wave in $(i \cos \Omega, i \sin \Omega)$ space. The end-point of this wave occurred when the particles had reached 1.242 AU. The forced elements at this point can be found fitting a circle to the distribution and finding the displacement of the center of this circle from the origin. Figures 4-3, 4-4, 4-5 and 4-6 show the variation with heliocentric distance of the forced elements $(i_p, e_p, \Omega_p, \varpi_p)$ respectively, for a source of Eos-type particles. Each diagram shows the forced elements for particles of diameter 4, 9, 14 and 25 μm . Notice in particular the effect of the strong inclination-type secular resonance at the inner edge of the asteroid belt on the forced inclinations shown in Figure 4-3. Larger particles are affected to a greater extent as their P-R drag decay rates are slower than for the smaller particles and they spend more time in the resonance region. Finally, polynomials can be fitted to the variation of each of the forced elements with heliocentric distance to facilitate their computation at any required semi-major axis.

Division of the Solar System

In order to investigate the spatial distribution of material in the model, space is divided into a three-dimensional array and the cross-sectional

contribution each orbit makes to each array element is calculated. The Solar System is divided up in spherical polar coordinates: r , the solar distance; θ , the ecliptic longitude; β , the ecliptic latitude. The model cloud is located within a space $(r_{\min}, r_{\max}; \theta_{\min}, \theta_{\max}; \beta_{\min}, \beta_{\max})$ which has been divided into a three-dimensional grid. The number of intervals along each of the three dimensions of the grid is denoted by nr , $n\theta$, $n\beta$ respectively. The coordinates of the vertices of the space cells, r_i, θ_j, β_k are tabulated, where i varies from 1 to $nr+1$; j from 1 to $n\theta+1$; k from 1 to $n\beta+1$.

Contribution of cross-sectional area from an individual orbit

Each point of intersection between the particle orbit and the cell walls is found. In the radial dimension, if perihelion is located in the i_1 th interval and aphelion in the i_2 th, then the number of wall-crossings in this dimension is given by $2(i_2-i_1)$ and all the r_i 's satisfying $r_{i_1} < r_i < r_{i_2}$ are the coordinates of the intersected walls. Similarly, the orbit occupies a space in ecliptic latitude between i and $-i$, and the corresponding boundary coordinates may be found using the same argument as for the radial dimension. All ecliptic longitude boundaries are intersected. The true anomaly, f , of the orbit is then found at each of these boundary intersection points. These are arranged in either monotonically increasing or decreasing order: each pair of adjacent f 's indicate a section of the orbit that falls into a single cell. The mean anomalies can be converted into eccentric anomalies E by solving Kepler's equation. Finally, for each of the non-empty cells, the amount of cross-sectional area deposited is given by

$$\Delta A = \frac{A_{tot}}{N} \frac{\Delta(E - e \sin E)}{2\pi} \quad 4.13$$

where

$$\Delta E = E_2 - E_1 - e(\sin E_2 - \sin E_1). \quad 4.14$$

This procedure is repeated for every orbit in the cloud, and the accumulated cross-sectional area in each cell is divided by the cell volume. The result of the modeling procedure is therefore a large three-dimensional array, each element of which contains the local cross-sectional area per unit volume of the cloud. As a test of the algorithm, Figure 4-7 shows the variation of cross-sectional area per unit volume deposited into the cells as a function of heliocentric distance. This variation should be inversely proportional with distance: a least-squares fit to the linear portion of the plot confirms that this is the case.

Line of sight integration

Consider an infinitesimal cross-sectional area ΔA in an elemental volume dv at a distance R from the Sun and at a distance r from the Earth. Then,

$$dA = \psi(R)dv \quad 4.15$$

where $\psi(r)$ is the tabulated cross-section density found in the above section. The flux density contributed by dA observed at the Earth at ecliptic latitude β and ecliptic longitude θ is given by

$$dS_\lambda(\beta, \theta) = \frac{B_\lambda(T(R))}{r^2} dA \quad 4.16$$

where the temperature of the particle $T(R)$ may be found from balancing the absorbed and emitted energies of the particle:

$$\int_0^{\infty} F(R, \lambda) \pi s^2 Q_{abs}(s, \lambda) d\lambda = \int_0^{\infty} 4\pi s^2 Q_{abs}(s, \lambda) \pi B_{\lambda}(T, \lambda) d\lambda. \quad 4.17$$

where $F(R, \lambda)$ is the solar irradiance at heliocentric distance R . The absorption efficiency $Q_{abs}(s, \lambda)$ of the particle depends on nature of the grain material and with a knowledge of the dielectric function of the material may be calculated from Mie theory (see below). The surface brightness contribution from dA is therefore follows from 4.15:

$$dI_{\lambda}(\beta, \lambda) = \frac{dS_{\lambda}(\beta, \theta)}{d\Omega} \quad 4.18$$

where $d\Omega$ is the solid angle subtended to the observer by dv . Since $dv = r^2 d\Omega dr$, the total surface brightness integral along the line of sight is given by

$$I_{\lambda}(\beta, \lambda) = \int_0^{r_{max}} \psi(R) B_{\lambda}(T(R)) dr \quad 4.19$$

where r_{max} is the distance at which the particle number density becomes negligible. In this manner, brightness profiles of the model cloud can be constructed to be compared with observations of the dust bands such as those made by IRAS.

Mie Theory

Composition of the dust band material

Equations 4.2, 4.3 and 4.17 all involve efficiency factors which characterize a dust particle's interaction with incident radiation and depend on the composition of the dust. The dust bands are a product of asteroidal collisions, so

it is assumed that the composition of the dust band material is the same the composition of their parent asteroids. Reflectivity studies indicate that asteroids fall into two main classes: the S-type asteroids, relatively bright with albedos of about 15% and spectral features indicative of silicate material; and the C-type asteroids, darker with albedos between 2-5% indicating a substantial carbonaceous component. A third class, the M-type asteroids, exists having albedos of about 10% and spectra suggestive of metallic substances, but only about 5% of all asteroids falls into this class. The Eos and Koronis asteroid families have members with spectra ranging from the S-type to intermediary between S and C, while the Themis family contains C-type asteroids.

Calculations of the optical properties of dust grains in the infrared have been hampered by the absence of dielectric functions (variation of polarizability of a solid with wavelength from which the refractive index can be calculated) for candidate grain materials. A generic dielectric function has been generated for silicate type material by Draine and Lee (1984) which is consistent with available laboratory measurements and astronomical observations (for example the $10\text{ }\mu\text{m}$ silicate feature). The material represented by this synthetic function is known as 'astronomical silicate' and will be the basis for all dust band models produced in the next chapter.

Calculation of efficiency factors

The problem of investigating the interaction (scattering, absorption, extinction) of a plane linearly polarized wave and an arbitrary sphere was first

solved by Mie (1908) and independently by Debye (1909). A more recent discussion is found in Bohren and Huffman (1983). A detailed investigation leads to the result that the cross-sectional area for the interaction of a spherical grain of radius s with radiation is not given by πs^2 but by $Q\pi s^2$ where the efficiency Q (≈ 1) depends on the nature of the grain (size, refractive index etc.) and the wavelength of the radiation. Separate efficiencies exist for extinction, absorption and scattering, and for a spherical grain

$$Q_{ext} = Q_{abs} + Q_{scat}. \quad 4.20$$

The solution for a spherical particle given by Mie theory expresses the scattering and extinction cross sections respectively as

$$C_{scat} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2) \quad 4.21$$

$$C_{ext} = \frac{2\pi}{k^2} \sum_{n=1}^{\infty} (2n+1) \operatorname{Re}\{a_n + b_n\}. \quad 4.22$$

Here,

$$k^2 = \omega^2 \epsilon \mu \quad 4.23$$

where ω is the angular frequency of the field, ϵ is the complex permittivity and μ is the permeability. The quantities a_n and b_n are the scattering coefficients, given by

$$a_n = \frac{m\Psi_n(mx)\Psi_n'(x) - \Psi_n(x)\Psi_n'(mx)}{m\Psi_n(mx)\xi_n'(x) - m\xi_n'(x)\Psi_n'(mx)} \quad 4.24$$

$$b_n = \frac{\Psi_n(mx)\Psi_n'(x) - m\Psi_n(x)\Psi_n'(mx)}{\Psi_n(mx)\xi_n'(x) - m\xi_n'(x)\Psi_n'(mx)} \quad 4.25$$

where primes indicate differentiation with respect to the argument in parentheses. The size parameter x and the relative refractive index m are given by

$$x = \frac{2\pi Ns}{\lambda}, \quad 4.26$$

$$m = \frac{N_1}{N} \quad 4.27$$

where N_1 and N are the refractive indices of the particle and medium respectively and s is the radius of the particle. The equations for the scattering coefficients have been simplified by introduction of the Ricatti-Bessel functions:

$$\Psi_n(\rho) = \rho j_n(\rho), \quad 4.28$$

$$\zeta_n(\rho) = \rho h_n(\rho) \quad 4.29$$

where j_n and h_n are spherical Bessel and Hankel functions respectively. Once the cross sections have been calculated, the efficiency factors are obtained straightforwardly from the cross sections:

$$Q_{scat} = \frac{C_{scat}}{\pi a^2}, \quad Q_{ext} = \frac{C_{ext}}{\pi a^2}, \quad Q_{abs} = \frac{C_{abs}}{\pi a^2}. \quad 4.30$$

Computation of the cross sections and the efficiency factors is performed using a FORTRAN code (Gustafson, private communication; Gustafson 1994) based around the BHMIE subroutine developed by Bohren and Huffman (1983).

Figure 4-8 shows the variation of Q_{abs} with wavelength for a range of particle sizes. Of the particles shown, the absorption efficiency peaks at 9 micron in the 25 micron wave band. The 10 and 20 micron silicate features are clearly

seen for the small particles, and become less pronounced as the particle size increases. The solutions for the largest sizes approach the asymptotic solution for an infinite size sphere, with the exception of the marked enhancement at longer wavelengths. Once Q_{abs} has been calculated equilibrium temperatures may be found via Equation 4-17. Figure 4-9 shows the variation of equilibrium temperature with heliocentric distance for a variety of particle sizes, along with the variation expected for a blackbody. While the large particle temperatures approach the blackbody limit, smaller particles are hotter since they have a lower average emissivity efficiency.

The Limitations of Mie Theory

Interplanetary dust particles (IDPs) which contribute to the infrared zodiacal signature are presumably not perfect spheres. Much is made in the literature of the 'fluffy' nature of IDPs, a prime example of which is the 'Bird's Nest' model for cometary dust (Greenberg and Gustafson 1981). To what extent, then, can the use of Mie theory be justified in investigating the interaction of non-spherical particles with solar radiation? One school of thought appears to oppose the use of Mie theory in any situation as a gross oversimplification, another seems to apply Mie theory readily with little thought to the physical consequences. Perhaps the key lies somewhere between these two extremes. Mie theory does provide a first order description of optical effects in non-spherical particles and correctly predicts many small particle effects which are not intuitively obvious. On the other hand recent laboratory microwave analog

experiments (Zerull et al. 1993) underline the extent to which Mie theory approximations fail to satisfactorily reproduce the total scattering functions of multiple sphere aggregates. The bottom line is that Mie theory still represents the only practical method for calculating the light scattering properties of finite particles of arbitrary size and refractive index.

In any case, the results presented in the following chapter are not critically dependent on the validity of Mie theory. Models of a single particle 'size' calculated via SIMUL actually depend only on the particle's β , the ratio of the radiation pressure to the gravitational force. Refinements in the calculation of temperatures and optical properties which have recently appeared in the literature (Xu 1995) and will develop in the near future will be applied to exactly the same models.

Table 4-1: The mean proper elements and their standard deviations of the three major Hirayama asteroid families.

Asteroid family	Semi-major axis (AU)	Eccentricity	Inclination (deg)
Eos	3.015 ± 0.006	0.071 ± 0.008	10.20 ± 0.28
Themis	3.148 ± 0.035	0.155 ± 0.013	1.426 ± 0.320
Koronis	2.876 ± 0.026	0.047 ± 0.006	2.112 ± 0.085

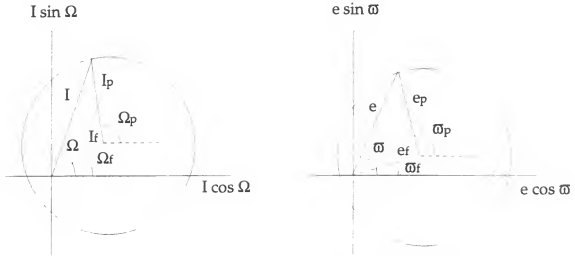


Figure 4-1: The vectorial relationship between the total (osculating) elements (i, e, Ω, ϖ), the proper elements ($i_p, e_p, \Omega_p, \varpi_p$) and the forced elements ($i_f, e_f, \Omega_f, \varpi_f$) in both ($e \cos \varpi, e \sin \varpi$) and ($i \cos \Omega, i \sin \Omega$) space. The distributions are displaced from the origin due to the forced elements and the radius of the distributions represents the proper elements.

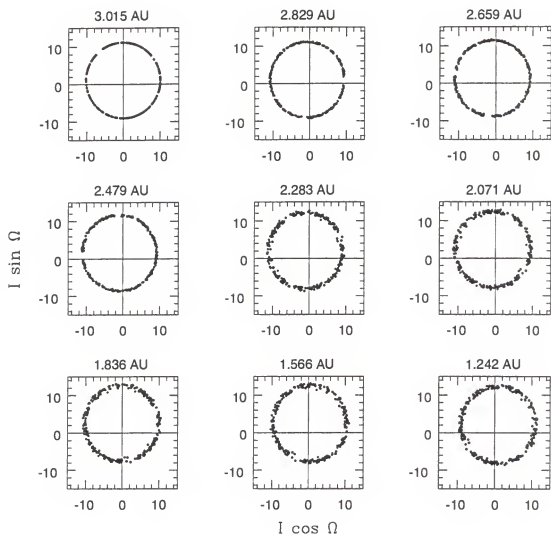


Figure 4-2: A demonstration of the calculation of forced elements via numerical integration. The figure shows the evolution of a wave of 10 micron diameter dust particles with Eos-type orbits in $(I \cos \Omega, I \sin \Omega)$ space. The endpoint of this wave occurred when the particles had reached 1.242 AU. The forced elements at this point can be found fitting a circle to the distribution and finding the displacement of the center of this circle from the origin.

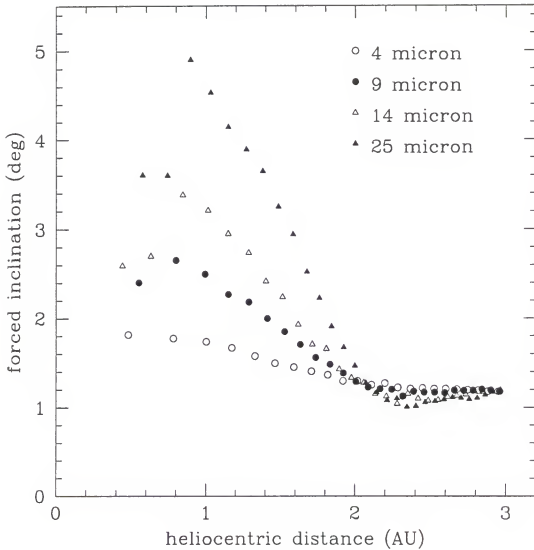


Figure 4-3: The variation of the forced inclination with heliocentric distance for four different sizes of dust particle having Eos-type initial orbits. Each point represents the endpoint of a wave of particles numerically integrated inwards as shown in Figure 4-2. The integrations were stopped at 1983, the year of the IRAS observations. Notice in particular the effect of the strong inclination-type secular resonance at the inner edge of the asteroid belt. Larger particles are affected to a greater extent as their P-R drag decay rates are slower than for the smaller particles and they spend more time in the resonance region.

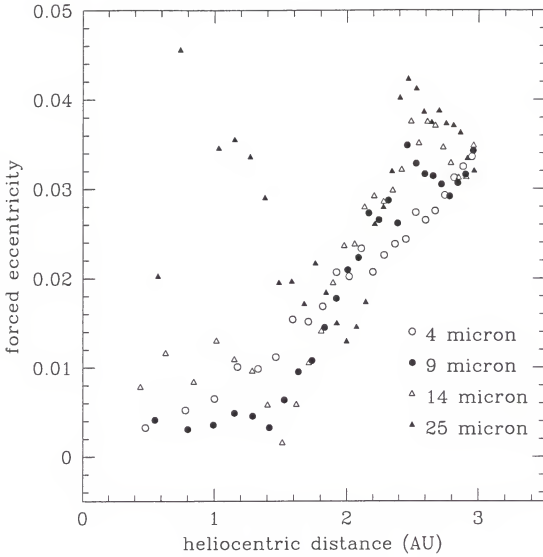


Figure 4-4: The variation of the forced eccentricity with heliocentric distance for four different sizes of dust particle having Eos-type initial orbits.

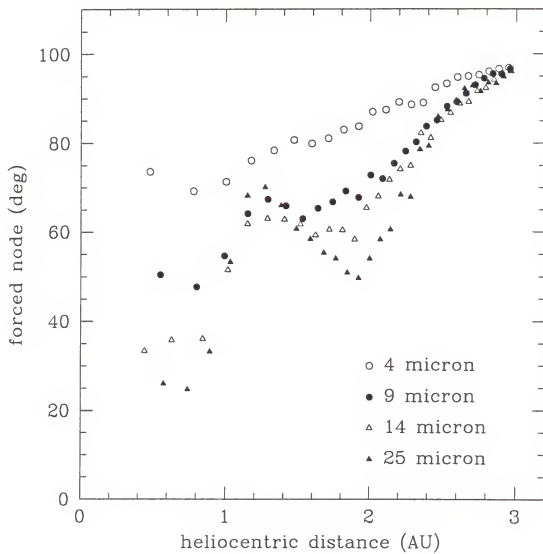


Figure 4-5: The variation of the forced node with heliocentric distance for four different sizes of dust particle having Eos-type initial orbits.

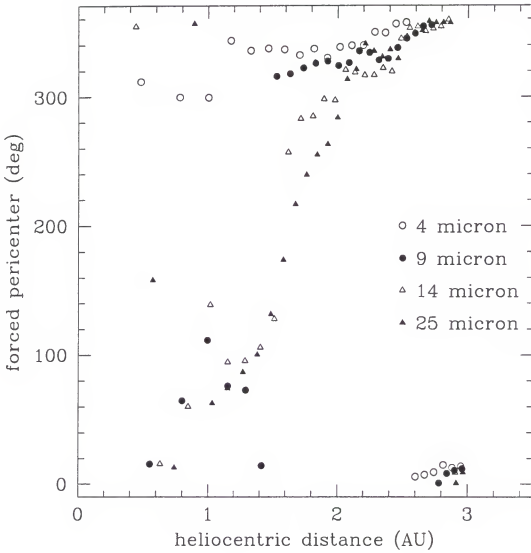


Figure 4-6: The variation of the forced pericenter with heliocentric distance for four different sizes of dust particle having Eos-type initial orbits.

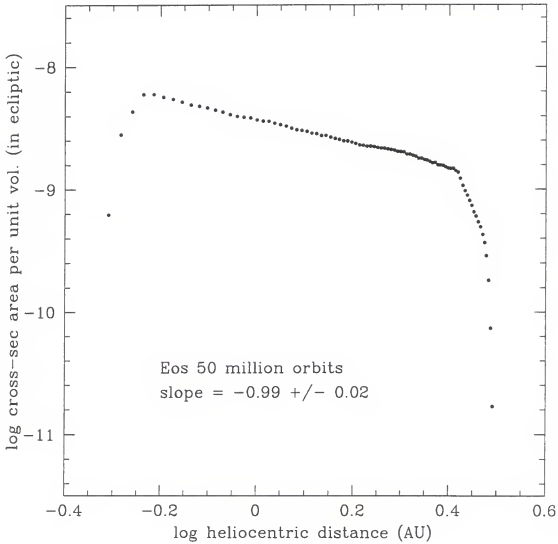


Figure 4-7: The variation of cross-sectional area per unit volume with heliocentric distance in an Eos dust band model created by SIMUL. The algorithm has populated the cells correctly - the variation is confirmed to be inversely proportional with distance.

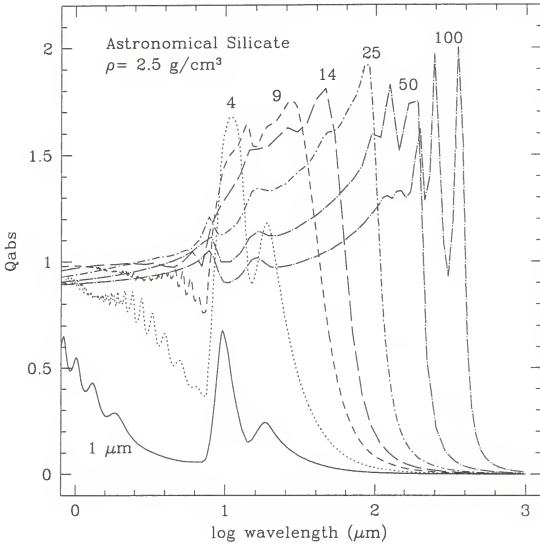


Figure 4-8: The variation of Q_{abs} with wavelength for astronomical silicate particles. Each curve represents a different particle size, the diameter of which is given by the corresponding label.

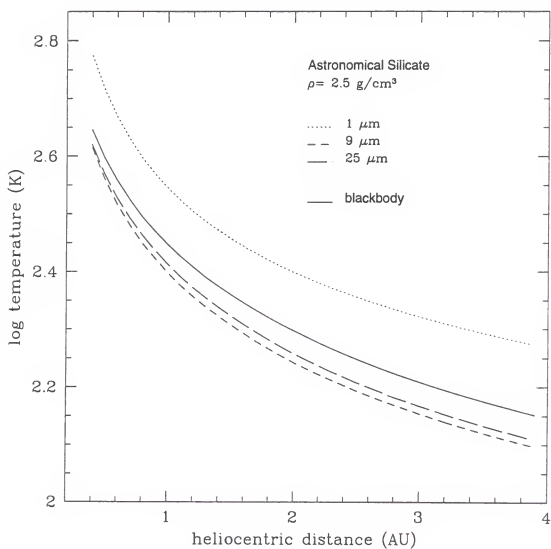


Figure 4-9: The variation of equilibrium temperature with heliocentric distance for astronomical silicate particles of different diameters, along with the variation expected for a blackbody.

CHAPTER 5 COMPARISON OF MODEL DUST BANDS WITH OBSERVATIONS

IRAS Observations of the Dust Bands

The viewing geometry of the IRAS spacecraft was ideal for the study of the zodiacal cloud. The Medium Resolution (2' in-scan) Zodiacal Observational History File (ZOHF) consists of 5757 sky brightness profiles, each providing a detailed view of the pole-to-pole cloud structure in a given line of sight defined by the ecliptic longitude of Earth and solar elongation angle in both the trailing and leading directions. The ZOHF covers nearly 300° of longitude of Earth, with most scans being taken at around 90° solar elongation. Towards the end of the survey the satellite was not restricted to elongation angles around 90° but covered elongations all the way from 60° to 120° . Unfortunately these observations were contaminated by Galactic noise as the Galactic plane was at this point close to the ecliptic. The results presented in this chapter shall concentrate on the 90° solar elongation data.

The changes in shape and flux of the dust band residuals are caused by a combination of the complex three-dimensional structure of the dust bands themselves and also the observing geometry of the IRAS satellite. The two primary causes for a change in the line of sight are (a) the longitude of the Earth and (b) the solar elongation angle. The changes due to these two parameters are

taken to be independent to the first order, allowing a quantitative parameter to be associated with each. Changes in elongation angle produce a parallax effect: there is a change in the effective distance to the bands, and for small changes in elongation angle the effect can be assumed to be linear. The slope $dy/d\varepsilon$ for the change in peak latitude of the north or south dust band β_N or β_S with elongation angle can be found from a number of scans of a given longitude of Earth with varying solar elongation and this used to normalize the peak latitude that would be observed at a solar elongation of 90° . Once this has been done, the normalized values of β_N , β_S may be used to obtain $\langle\beta\rangle$, the mean north/south peak latitude, which may be plotted as a function of the longitude of Earth. This is shown for the 25 micron wave band in Figure 5-1. The sinusoidal variation indicates that the plane of symmetry of the bands, the plane about which on average the proper inclinations of the particles precess, is inclined to the ecliptic. This tilt of the plane of symmetry is due to the secular perturbations of the planets, and its orientation depends on the forced elements imposed on the dust particles. When viewed from Earth such a plane would appear as a sine curve, its amplitude equal to the inclination of the plane. Also, the displacement from the ecliptic will be equal in the trailing and leading directions at the ascending and descending nodes. Profiles of different longitudes of Earth can now be coadded using the parameters of this sine curve representing the variation of peak latitude of the bands due to their plane of symmetry being inclined to the ecliptic; this effect

translates into a lateral shift that can be positive or negative depending on the longitude of Earth, and a minimum when Earth is at the forced nodes.

Individual IRAS scans were fast Fourier filtered as outlined in chapter 3 and the dust band residuals coadded in the above manner to produce several representative dust band profiles around the sky normalized to a solar elongation angle of 90° with noise levels an order of magnitude lower than the original scans. The results of this process for the 12, 25, 60 and 100 micron wavebands, leading and trailing, are shown in Figures 5-2 through 5-9. The 100 micron observations are dominated by Galactic noise to the extent that identification of dust bands is impossible, and these observations will be discarded in the subsequent analyses.

The dust band emission peaks in the 25 micron waveband, although the dust bands are still clearly visible at 12 and 60 microns. The dust bands have a lower amplitude but similar shape at 12 microns compared to 25 microns, whereas at 60 microns the central band is less prominent with respect to the ten degree band than when viewed at the shorter wavelengths. The differences in the shapes of the bands as seen in the different wavebands is clearly evident in Figures 5-10 and 5-11, where the 25 micron leading observations are shown along with the 12 and 60 micron leading observations respectively, scaled such that the amplitudes of the ten degree bands in both wavebands are equal. Corresponding diagrams for the trailing observations are shown in Figures 5-12 and 5-13. There are real, although subtle, differences evident in the shapes of the 25 and 12

micron central bands as seen in Figure 5-10, and more dramatic differences in the 25 and 60 micron bands seen in Figure 5-11. This underlines the point that different material within the dust band structure is revealed when observing in different wavebands.

These observations contain a wealth of information about the structure of the dust bands; certain aspects, however, deserve special mention. Firstly, there exists a sinusoidal variation in the latitudes of peak brightness of the north and south ten degree band pair around the sky. This is due to the forced inclinations imposed on the dust band particle orbits by planetary gravitational perturbations (Dermott et al. 1993). Secondly there is a clear split in the central band and the amplitudes of each peak vary around the sky. The amplitudes of the north and south ten degree band pair also undergo such a variation except that this variation seems to be out of phase with the variation seen in the corresponding north and south peaks of the central band. The complex structure revealed by these observations underlines the point that empirical models which attempt to describe the zodiacal cloud as a whole will always fall hopelessly short in accounting for features such as these, and the problem demands a detailed dynamical treatment.

Modeling the Dust Bands

The equilibrium model for the dust bands suggests that the three major Hirayama asteroid families, Themis, Koronis and Eos, provide the source for the

dust band structures seen in the IRAS observations. A simple model for the dust bands is therefore constructed using the SIMUL model as outlined in chapter 4. The ten degree band pair is modeled by populating the asteroid belt with a large number of dust particle orbits (several million are used in the model) with mean semi-major axis, proper eccentricity, proper inclination and corresponding dispersions equal to those of the Eos asteroid family. In a similar fashion, a central band is created by including material with orbital elements corresponding to the Themis and Koronis families. The iterative filtering procedure explained in chapter 3 is then applied to dust band profiles obtained from this model, and the resultant filtered model profile compared to the corresponding IRAS observation. A comparison for one such profile is shown in Figure 5-14. Although the model central band compares favorably with the observed central band, it is clear that the simple ten degree band model derived from the Eos family member type orbits and their orbital element dispersions fails with respect to both the shape of the band and the latitudes of peak intensity. A natural question is raised: Is Eos really the source of the ten degree band? Dermott et al. (1990) suggested that increasing dispersions in the orbital elements of dust band particles would alter the shape and latitudes of the dust band profiles. The extent to which an increase in the dispersion of the orbital inclinations of the dust band particles can address the discrepancies in the Eos-based ten degree model is now investigated.

The effect of dispersion on dust band profiles

A link between the Eos family and the ten degree band can be maintained if a dispersion in the proper orbital inclinations of the dust band particles is invoked that is higher than that of the Eos family member asteroids themselves. There is no compelling reason to assume that the dust band material contributing to the thermal emission at, for example, 25 micron and having diameters of order 1-100 microns should have the same dispersion in orbital inclination as the kilometer-sized members of the Eos asteroid family. The smaller material is subject to significant Lorentz forces and has a different collisional history. Figure 5-15 shows a raw (unfiltered) model profile produced from material having Eos family member type orbital elements and a dispersion in proper inclination of 0.3° , the dispersion in proper inclination of the Eos family. The effect on the shape of the profile as the dispersion in proper inclination is increased is also shown. An ideal dust band consists of particles with identical proper inclinations, a common forced inclination, identical forced nodes and uniformly distributed proper nodes. The resultant profile is sharp with straight edges. However, as the dust band material becomes dispersed in proper inclination, the dust band profiles are broadened and the latitude of peak intensity moves in towards the ecliptic. Both of these effects serve to address the discrepancies raised with the standard, low proper inclination dispersion ten degree model.

From the above investigation of the effect of dispersion on the model dust profiles, it is found that if the Eos type material is confined to the asteroid belt

(semi-major axis > 2.0 AU), a dispersion in proper inclination of the dust band material of approximately 2.5° is required to match the model profiles with observations. Figures 5-16 and 5-17 show the same 25 micron IRAS observations as Figures 5-4 and 5-5, and overlaid are corresponding profiles produced from a dust band model including Eos material with 2.5° dispersion in proper inclination. The Themis and Koronis material making up the central band remains the same as that included in the original low dispersion model, and the surface area of dust in each family, given in Table 5-1, has been adjusted to best fit the amplitudes of the observed dust band profiles. All profiles have a peak amplitude of around 2 MJy/Sr, and both trailing and leading profiles have been arranged on one diagram each for convenience. A dashed vertical line is placed at $\pm 10^\circ$ for reference. The primary criterion for matching the two is a match in the latitude of peak intensity of the ten degree band pair. The dispersion in proper inclination is increased until the peak latitudes have moved in towards the ecliptic to match the observed peak latitudes. The argument is made more persuasive by the fact that the shapes of the bands now show a convincing match with the observations. Indeed, the numerical models show that it is impossible to reproduce ten degree bands of the observed shape without invoking this increase in dispersion. It would be possible to match the latitudes of peak intensity of the band pair with a hypothetical family with a mean proper inclination of approximately 8.5° having low dispersion in inclination, but the shape of the profiles would be too peaky. To match the shape of the observed bands a high

dispersion is required; this places the source material firmly at the latitude of the Eos family.

Figures 5-18 to 5-21 show the 12 and 60 micron model profiles from the 2.5° model discussed above. Although the shapes of the 12 micron models are consistent with the observations, the 60 micron models are consistently lower in amplitude than their corresponding observations. This is perhaps to be expected: the dust band models discussed so far are composed of one particle size, 9 micron. While these particles could be expected to contribute strongly to the 12 and 25 micron wavebands, the contribution from these particles to the 60 micron wave band will be less. If, in fact, the surface area associated with the 9 micron particle models is increased from the values given in Table 5-1 by a factor of three, the 60 micron models fit the observations much better, as shown in Figures 5-22 and 5-23.

Sykes (1990) also discusses the effect of dispersion on the dust band profiles, and reports that his dust band residuals are best fit with a dispersion in orbital inclination of approximately 1.4°. This result, however, is based on an empirical fit of the high-frequency component of the dust band alone, since the question of the low-frequency component of the dust band contained in the background is left unanswered.

Populating the inner solar system

Much of the emission from the material that constitutes a toroidal dust band is lost in the background emission separated by the filtering process. This

effect is exacerbated when a dispersion is imposed on the dust band material. As the dispersion is increased, and the profiles become broader, the broadscale component of the dust band increases and the filter associates more and more of the emission from the dust band material with the zodiacal background. Therefore in order to retain filtered dust band profiles with the same intensity as the observed profiles, additional material has to be pumped into the model dust bands.

In addition to the 2.5° model discussed above, a model has also been constructed which allows this Eos-type asteroidal material to populate the inner solar system by a Poynting-Robertson drag distribution. The incentive is that some fraction of asteroidal material must reach Earth's orbit owing to the existence of Earth's resonant ring (Dermott et al. 1994b). Because of a parallax effect, the latitudes of peak intensity of the ten degree band pair in this new model increase. To maintain the band pair at the observed latitude, the dispersion in proper inclination must be increased to approximately 3.5° . The resulting profiles in the 25 micron wave band from this new 3.5° model are presented in Figures 5-24 and 5-25. Close examination of the model profiles reveals that they are slightly broader than the observed profiles. If the variation of the number density of asteroidal material with heliocentric distance r is given by an expression of the form $1/r^\gamma$ then these results indicate that $\gamma < 1$ compared with $\gamma = 1$ expected for a simple Poynting-Robertson drag distribution. This implies that asteroidal material is lost from the system, perhaps due to

interparticle collisions, as it spirals in towards the Sun. This in turn has implications for the size-frequency distribution in the zodiacal cloud: if particles do not survive intact from source to sink then the size-frequency distribution should not be constant with heliocentric distance but vary in some smooth manner. This is apart from the fact that different particles will have different P-R drag rates; in effect the smaller particles will be filtered out from the local distribution faster.

There is evidence for a variation in the size-frequency distribution. Using the cratering record on the LDEF satellite, Love and Brownlee (1993) find that the surface area of zodiacal cloud particles at 1 AU is concentrated in large particles rather than small ones. Figure 5-26 shows that the surface area contribution peaks at a particle diameter of approximately 100 microns. The slope of the linear portion of the curve between 10 and 100 microns indicates a value of the size-frequency index q at 1 AU of approximately 1.1, as opposed to the classical collisional equilibrium value of 1.83 (Dohnanyi 1969) which may be expected in the source region of the asteroid belt.

Implications for the asteroidal component of the zodiacal cloud

Figure 5-27 shows the level of emission produced from two unfiltered dust band profiles, one taken from the 2.5° model, the other from the 3.5° model. The corresponding IRAS profile is also shown for comparison. Table 5-1 shows the amount of Eos, Themis and Koronis material used in the models in terms of the surface area contribution from each family. Also shown is the contribution

from each family to the peak flux observed by IRAS. Figure 5-25 shows that the peak dust band emission from the 2.5° model is approximately 5% of the peak zodiacal background emission. However, the emission from the 3.5° model is significantly higher with appreciable emission at the ecliptic poles and a peak intensity approximately 25% that of the zodiacal background. This is because the material populating the inner solar system is warmer and closer to Earth. It has been calculated that the ratio of dust production by asteroid families to dust production by all asteroids as approximately 1:3 (Durda and Dermott 1997). This would imply that based on the dust band models presented in this chapter, up to 75% of the zodiacal cloud, in terms of the material which gives rise to the thermal emission produced in the 25 micron waveband, may be asteroidal. The actual contribution probably lies somewhere between the two extremes suggested by the 2.5° and 3.5° models. Whereas the IRAS observations are concentrated at around 90° in solar elongation, the COBE observations have a wide range of solar elongation angle (64° to 124°) and future analysis of the COBE data will provide valuable information on the distribution of material throughout the inner solar system and serve to constrain the dust band models further.

The role of a size-frequency distribution

The zodiacal cloud complex is not simply a distribution of 9 micron diameter dust particles. The population will be the product of catastrophic collisions of larger asteroids (Davis et al. 1979). Although the nature of the resultant size-frequency distribution of collision products will be complex, for

example it will most certainly vary as a function of heliocentric distance as a result of different P-R drag rates for different sized particles (Gustafson et al. 1992), the size-frequency distribution can be most simply described by an expression of the form

$$\frac{dN}{d \ln D} = \left(\frac{D}{D_0} \right)^{-p}, \quad 5.1$$

$$dN = D_0^p D^{-(p+1)} dD, \quad 5.2$$

and the cumulative number greater than D ,

$$N_{cum} = \int_D^{D_{max}} D_0^p D^{-(p+1)} dD. \quad 5.3$$

If $D \ll D_{max}$ and $p > 1$,

$$N_{cum} = \frac{1}{p} \left(\frac{D_0}{D} \right)^p. \quad 5.4$$

From Equation 5.2, if dN is the number of particles in a bin of width dD and each particle has an area $(\pi/4)D^2$, then the area of particles in the bin,

$$dA = \frac{\pi}{4} D_0^p D^{-(p-1)} dD. \quad 5.5$$

The cumulative area of particles $> D$,

$$A_{cum} = \frac{\pi D_0^p}{4(p-2)} \left[D^{-p+2} \right]_D^{D_{max}}. \quad 5.6$$

If $p > 2$ then the area is in the small particles and A_{cum} is independent of D_{max} ,

$$A_{cum} = \frac{\pi D_0^p}{4(p-2)} D^{-(p-2)}. \quad 5.7$$

The theoretical equilibrium solution (Dohnanyi 1969) has a population index $q=1.83$ where

$$p = 3(q - 1). \quad 5.8$$

To construct dust band models with a size-frequency distribution, the approach should be to produce separate model dust band profiles for different particle sizes, then add them together weighted by Equation 5.5, which dictates how much surface area resides in each size bin. Sensible upper and lower limits on the particle sizes included would seem to be dictated by those particles contributing to the thermal emission in the wave bands under consideration. There are, however, other factors to be considered. Figure 5-28 shows the variation of β (ratio of radiation pressure to gravitational force) with size for astronomical silicate particles having a density of 2.5 g/cm^3 . For eccentricities $e > 1-2\beta$ the kinetic energy for particles set free in perihelion exceeds the magnitude of the potential energy (Leinert and Grün 1990). Effectively then, particles with $\beta > 0.5$ are blown out of the Solar System. Notice that there are two size regimes in which particles can survive radiation pressure: diameters greater than approximately 1 micron and less than approximately 0.1 micron (small particles have decreasing radiation pressure efficiency Q_{pr}). However, Figure 5-29 shows that particles of approximately 0.1 micron and smaller do not contribute significantly to the thermal emission in the 25 micron wave band as their absorption efficiency Q_{abs} decreases. Figure 5-30 shows the cumulative flux expected with particle size for the three wave bands under consideration. This

assumes a particle source located at 3 AU with a size-frequency index $q=1.83$. Flux contributions to the 12 and 25 micron wave bands begin to level off at a particle diameter of approximately 0.1 micron, and contributions to the 60 micron wave band begin to level off at a particle diameter of approximately 10 microns. For these reasons, the range of particle sizes included in the size-frequency distributions to follow is taken to have a small particle cut-off at 1 micron diameter, and a large particle cut-off at 100 microns due to collisional lifetime considerations (Leinert and Grün 1990).

The origin of the dispersion in orbital inclinations

The best fit models for the Eos dust band discussed earlier required a dispersion in orbital inclination of 2.5° . Is this an intrinsic dispersion within the family, in other words a dispersion which reflects the source distribution of material, or does the dispersion depend on some physical mechanism dependent on the particle size? The most obvious candidate for a mechanism to produce dispersion in orbital inclinations is the Lorentz force. Particles in low inclination orbits experience alternating signs of the Lorentz force because of the interplanetary sector structure where the polarity of the magnetic field alternates between adjacent sectors (Leinert and Grün 1990). Stochastic variations in sector length leads to a random walk in inclination of the particle orbit, such that the root mean square of the dispersion will increase with the square root of the distance traveled, and will be inversely proportional to the cube of the radius of the particle. Morfill and Grün (1979) report a value of 0.3° for a particle of 1

micron radius by the time it has spiraled in to 1 AU from the asteroid belt after 3000 years. However, subsequent treatments by Consomagno (1979), Barge et al. (1982) and Wallis and Hassan (1985) differ by more than an order of magnitude due to lack of detailed knowledge of the magnetic field structure.

The approach here is to assume a Lorentz force which produces a dispersion in inclinations of the form described above, but to calibrate the strength of the force such that the degree of dispersion produces a match to the observations. Figure 5-31 shows three such models, confined to the asteroid belt, produced such that the Lorentz dispersion has increased to 2.5° , 3.0° and 3.5° by the time the particles have reached the edge of the asteroid belt at 2 AU. These are shown with the a profile from the original best fit 2.5° model. It can be seen that a Lorentz dispersion of approximately 3.0° closely matches the original model. Figure 5-32 shows the result of combining 16 separate Eos dust band profiles representative of particle sizes between 1 and 100 microns according to a size frequency distribution with index $q=1.83$, and filtering, in order to compare the result with the IRAS observations. The 3.0° Lorentz dispersion is assigned to the 1 micron particles, the smallest particle size in the distribution. Although the majority of the total surface area is concentrated in the 1 micron particles (approximately 80%), the remainder is assigned to larger particles by the size-frequency distribution. Because of the strong inverse dependence of the Lorentz dispersion with particle size, the large material has little dispersion, and shows up as a peaky structure, similar to that shown in Figure 5-14. This could indicate

that (1) the size-frequency index of 1.83 is too small and there are even more small particles in the distribution than expected for collisional equilibrium or (2) the strength of the Lorentz dispersion is stronger than assumed here or (3) a Lorentz dispersion of the type modeled here is not the source of the dispersed Eos dust band and the dispersion is actually more representative of the source distribution.

Figures 5-33, 5-34 and 5-35 show the results of applying a size-frequency distribution with index $q=1.83$ to the best fit 2.5° model, in the 12, 25 and 60 micron wave bands respectively. The models match the observations in each wave band satisfactorily in terms of shape. However, although the values of surface area associated with the 12 micron wave band are the same as those found in Table 5-1, the 25 micron models require three times this area and the 60 micron models nine times this area to match the observed and model band amplitudes. In order to simultaneously match the amplitudes in all three wave bands the size-frequency index q has to be reduced to 0.83, the value expected for a system evolved under the effects of P-R drag as the smaller particles are removed at a rate inversely proportional to the particle size. This is evidence that more large material should be included in the modeling and is consistent with the picture from the LDEF cratering record that the size-frequency distribution varies with heliocentric distance and larger material dominates in the inner solar system.

Table 5-1: Asteroid family contributions to both the raw dust band models and the peak flux observed by IRAS.

Asteroid family	Area of dust used (10^9 km^2)	Contribution to flux observed by IRAS at 0° latitude	
		2.5° model	3.5° model
Eos	6.0	4%	22%
Themis	0.53	0.5%	2%
Koronis	0.53	0.5%	2%

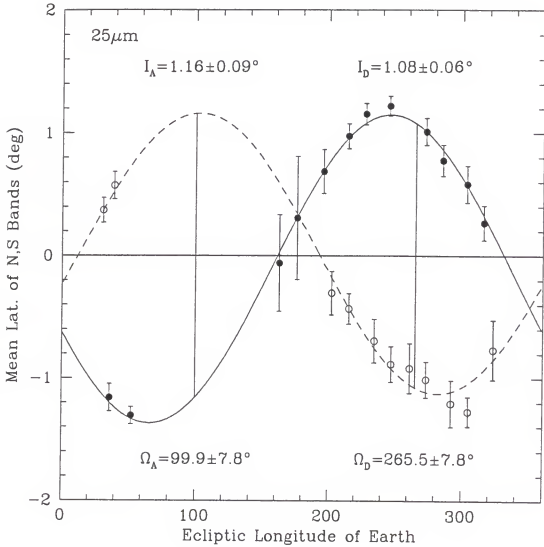


Figure 5-1: The variation of the mean of the north and south ten degree band peak latitudes in the 25 micron wave band with ecliptic longitude of Earth. The sinusoidal variation indicates that the plane of symmetry of the bands is inclined to the ecliptic. The amplitude of the variation is slightly more than one degree - close to the inclination of Jupiter's orbit. This is an indication that the material associated with the bands is located in the asteroid belt.

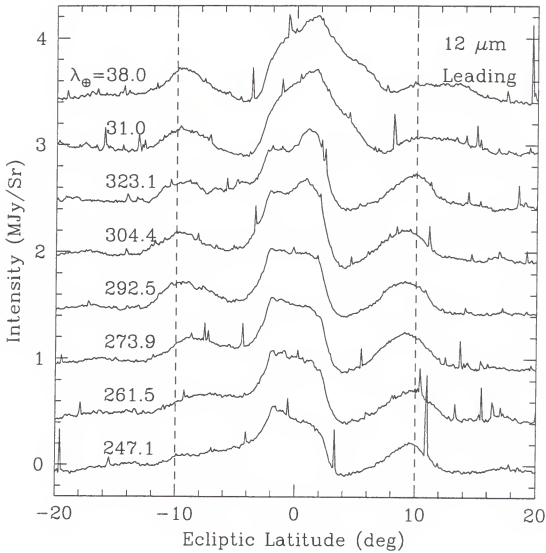


Figure 5-2: Coadded IRAS dust band profiles as seen in the 12 micron waveband at an elongation of 90° in the leading telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference.

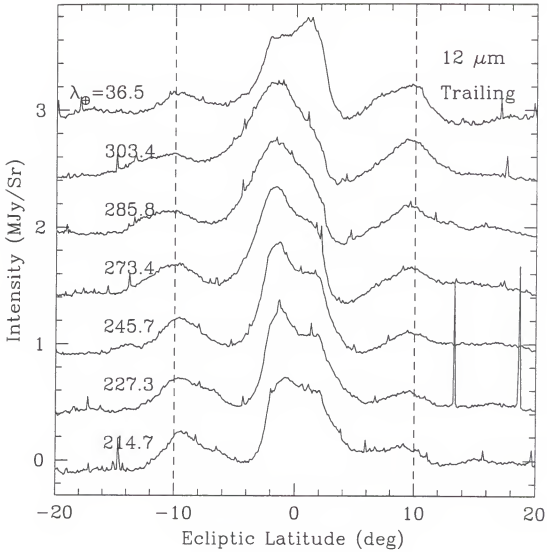


Figure 5-3: Coadded IRAS dust band profiles as seen in the 12 micron waveband at an elongation of 90° in the trailing telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference.

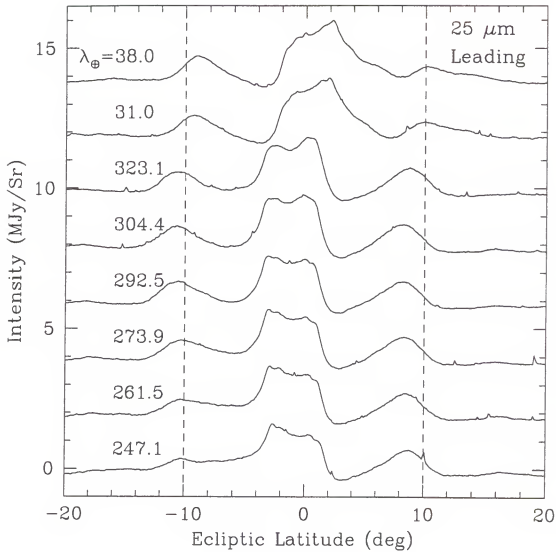


Figure 5-4: Coadded IRAS dust band profiles as seen in the 25 micron waveband at an elongation of 90° in the leading telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The zodiacal cloud signal peaks at this wavelength.

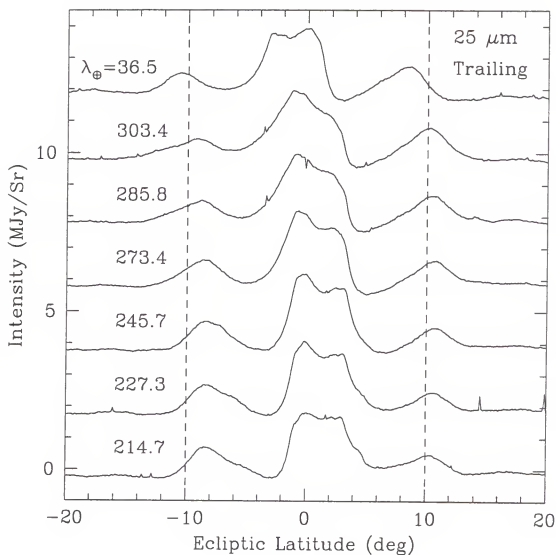


Figure 5-5: Coadded IRAS dust band profiles as seen in the 25 micron waveband at an elongation of 90° in the trailing telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The zodiacal cloud signal peaks at this wavelength.

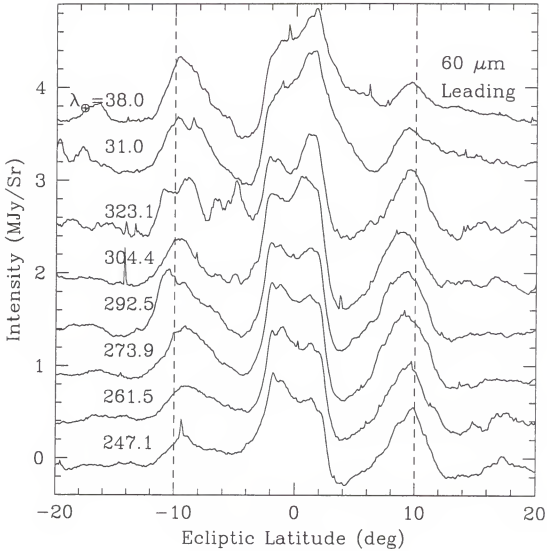


Figure 5-6: Coadded IRAS dust band profiles as seen in the 60 micron waveband at an elongation of 90° in the leading telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The central band becomes less prominent with respect to the ten degree band than for the shorter wavelengths.

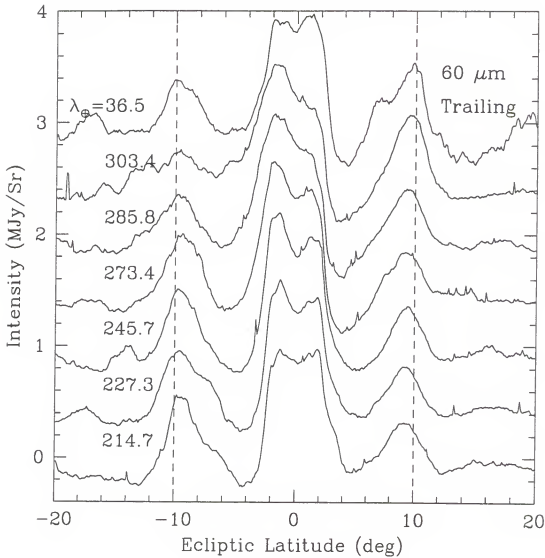


Figure 5-7: Coadded IRAS dust band profiles as seen in the 60 micron waveband at an elongation of 90° in the trailing telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The central band becomes less prominent with respect to the ten degree band than for the shorter wavelengths.

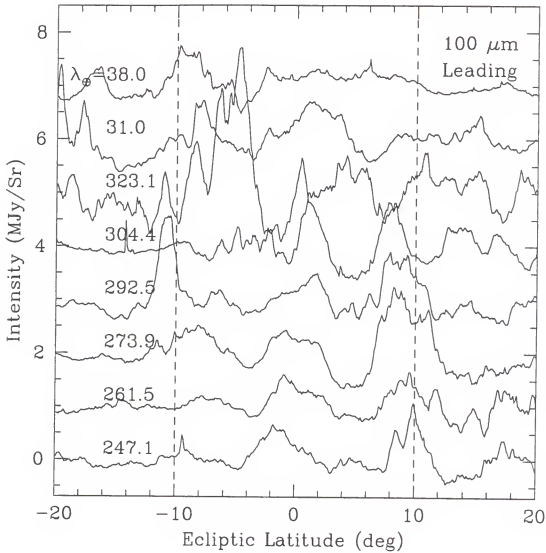


Figure 5-8: Coadded IRAS dust band profiles as seen in the 100 micron waveband at an elongation of 90° in the leading telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Galactic noise dominates making dust band identification difficult.

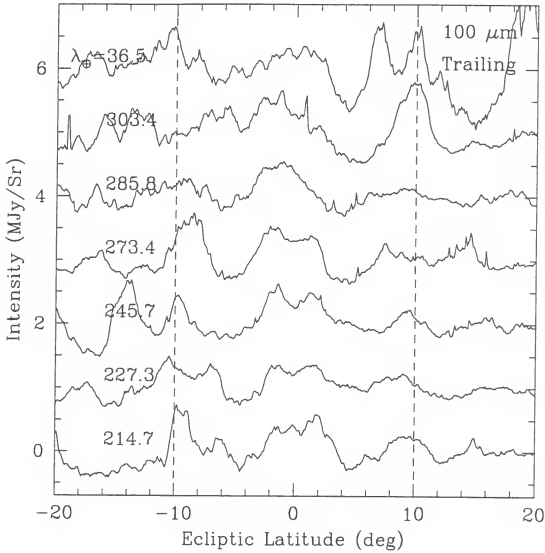


Figure 5-9: Coadded IRAS dust band profiles as seen in the 100 micron waveband at an elongation of 90° in the trailing telescope direction. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Galactic noise dominates making dust band identification difficult.

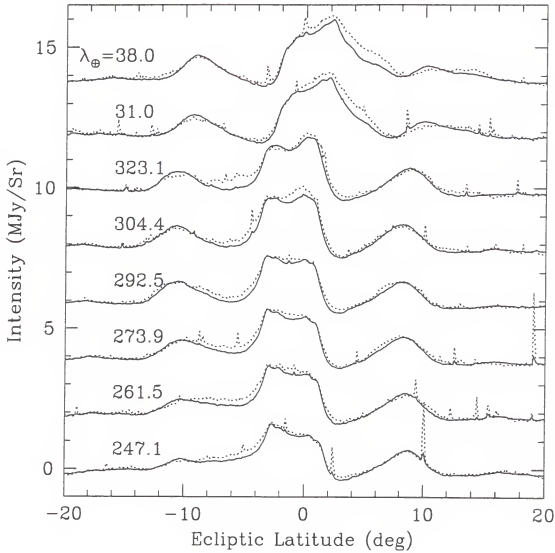


Figure 5-10: Differences in the material viewed in different wavebands. The 25 micron leading observations shown in Figure 5-4 are compared to the corresponding 12 micron observations, these shorter wavelength observations having had their amplitudes multiplied by a factor of three (to match the amplitudes of the ten degree bands). Subtle differences in the central band structure are evident.

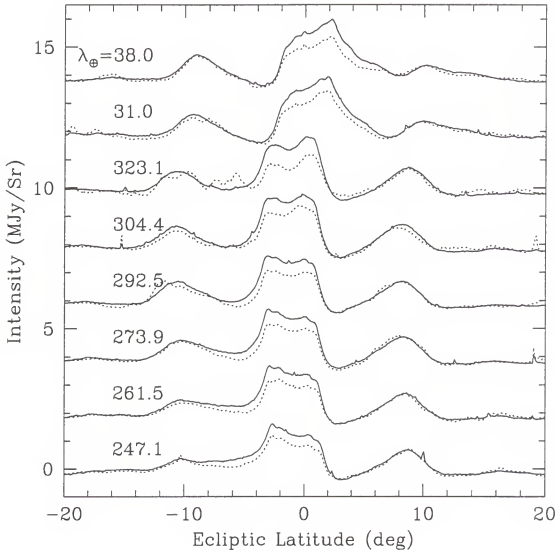


Figure 5-11: Differences in the material viewed in different wavebands. The 25 micron leading observations shown in Figure 5-4 are compared to the corresponding 60 micron observations, these longer wavelength observations having had their amplitudes multiplied by a factor of 1.3 (to match the amplitudes of the ten degree bands). The 60 micron central bands clearly have less power than their 25 micron counterparts.

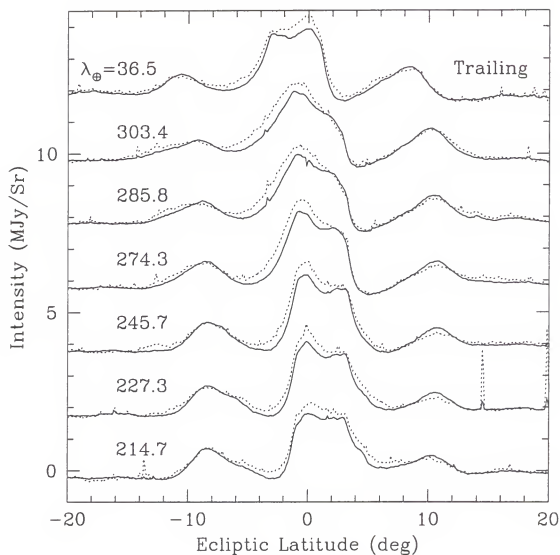


Figure 5-12: Differences in the material viewed in different wavebands. The 25 micron trailing observations shown in Figure 5-5 are compared to the corresponding 12 micron observations, these shorter wavelength observations having had their amplitudes multiplied by a factor of three (to match the amplitudes of the ten degree bands). Subtle differences in the central band structure are evident.

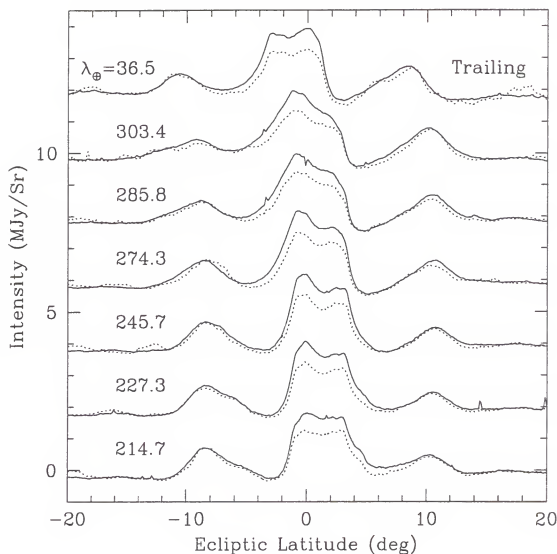


Figure 5-13: Differences in the material viewed in different wavebands. The 25 micron trailing observations shown in Figure 5-5 are compared to the corresponding 60 micron observations, these longer wavelength observations having had their amplitudes multiplied by a factor of 1.3 (to match the amplitudes of the ten degree bands). The 60 micron central bands clearly have less power than their 25 micron counterparts.

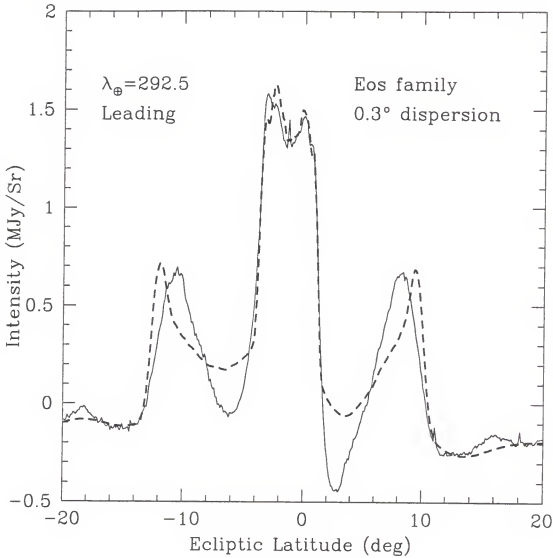


Figure 5-14: A simple model for the dust bands can be constructed using Eos, Themis and Koronis type material having orbital elements and dispersions in those elements equal to those of the corresponding asteroid family members. A sample profile from such a model is shown (dotted line) with the corresponding observed profile (solid line). The model profile is too peaked and has higher peak latitudes than the observed profile.

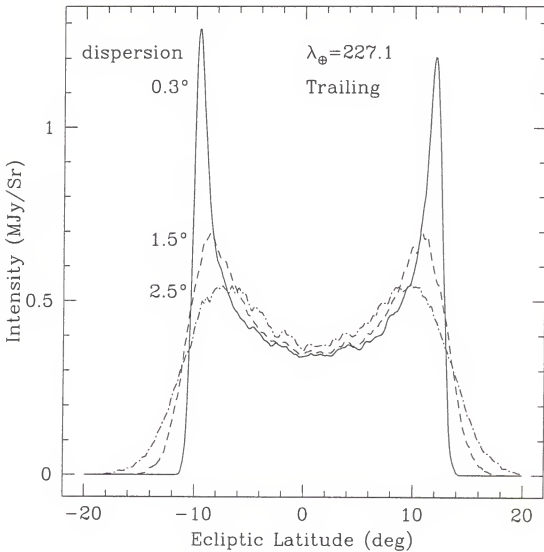


Figure 5-15: The effect of dispersion in the proper orbital inclination of the dust band material on the raw (unfiltered) dust band profiles. As the dispersion increases, the profiles become broader and the peak latitudes move in towards the ecliptic. Both of these effects serve to address the discrepancies evident in the standard, low inclination dispersion Eos model shown in Figure 5-14.

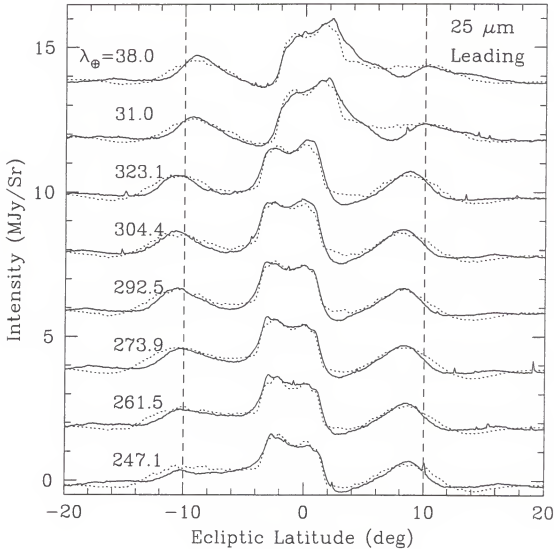


Figure 5-16: The observed 25 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The major features of the observed profiles are reproduced by the model.

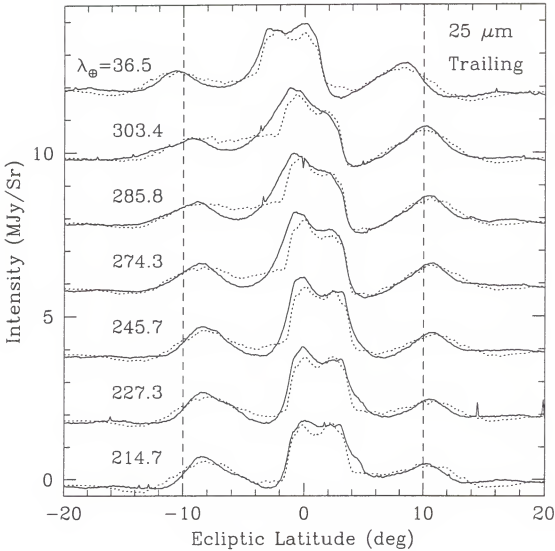


Figure 5-17: The observed 25 micron IRAS dust band profiles (solid lines) in the trailing direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The major features of the observed profiles are reproduced by the model.

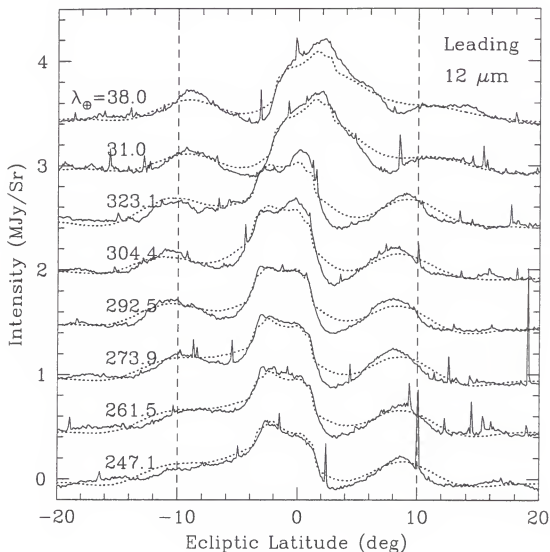


Figure 5-18: The observed 12 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Overall, the shapes of the models are consistent with the observations.

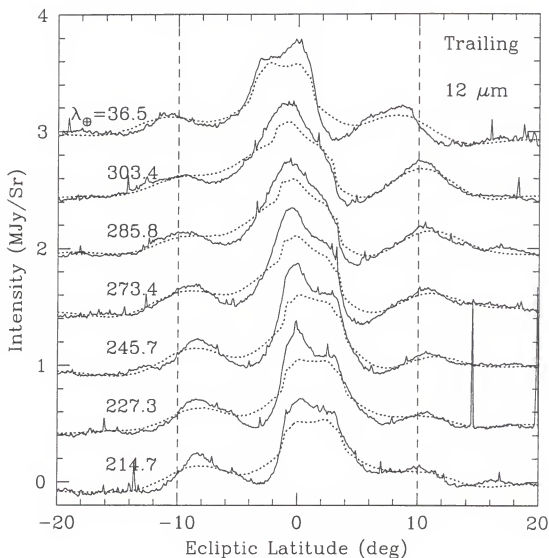


Figure 5-19: The observed 12 micron IRAS dust band profiles (solid lines) in the trailing direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Overall, the shapes of the models are consistent with the observations.

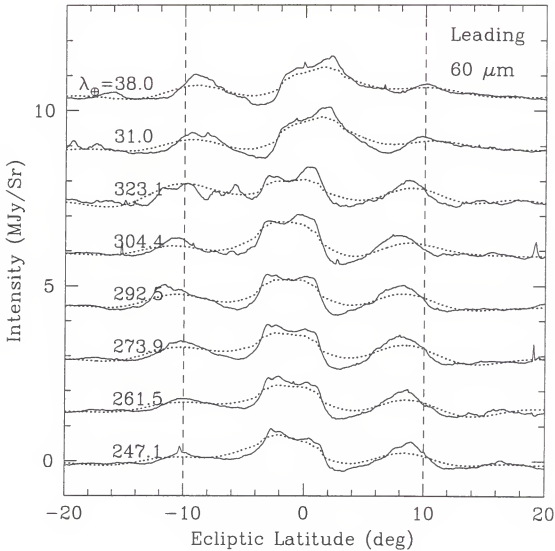


Figure 5-20: The observed 60 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The amplitudes of the model dust bands are consistently lower than the observations.

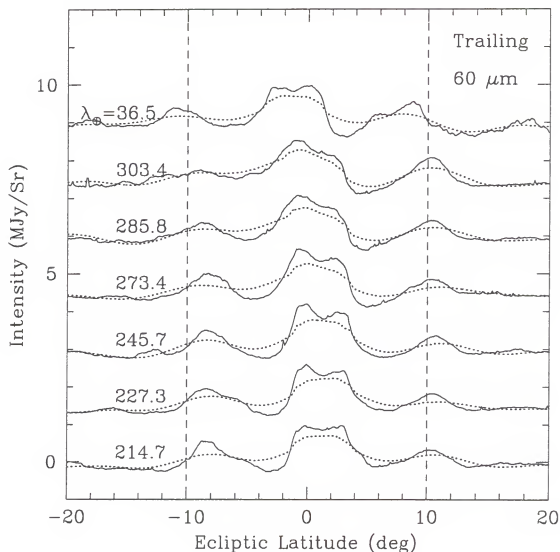


Figure 5-21: The observed 60 micron IRAS dust band profiles (solid lines) in the trailing direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The amplitudes of the model dust bands are consistently lower than the observations.

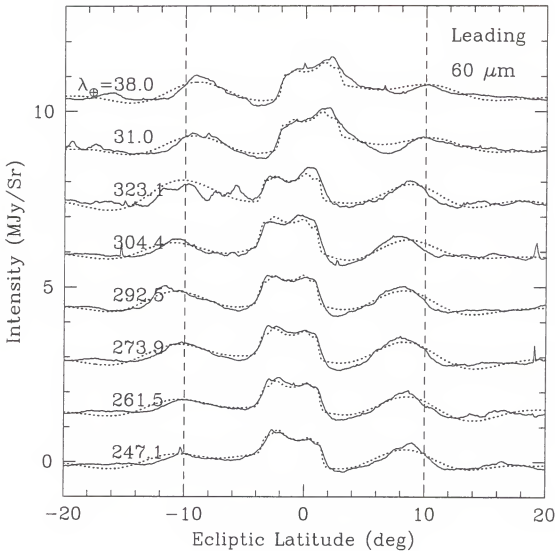


Figure 5-22: The observed 60 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface areas of material associated with each family are three times the values given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The increased surface area produces a better fit to the observations compared to Figure 5-20.

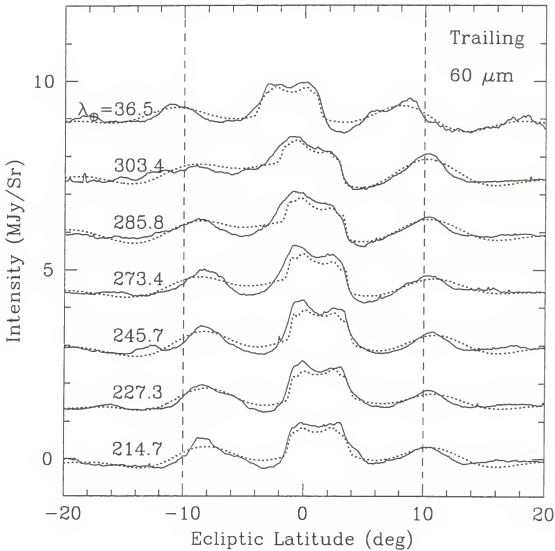


Figure 5-23: The observed 60 micron IRAS dust band profiles (solid lines) in the trailing direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits of 9 micron diameter particles confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. The surface areas of material associated with each family are three times the values given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. The increased surface area produces a better fit to the observations compared to Figure 5-21.

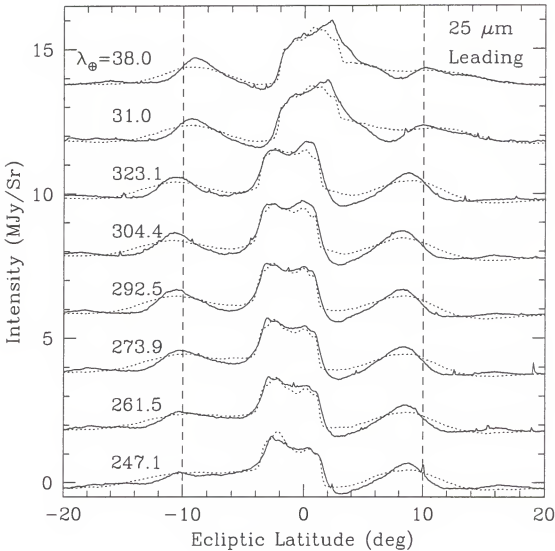


Figure 5-24: The observed 25 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits allowed to spiral into the inner solar system via P-R drag. Because of a parallax effect the latitudes of peak intensity move away from the ecliptic, and to preserve the model peak latitudes at the observed values, the dispersion in the orbital inclinations of the Eos material is increased to 3.5° . Themis and Koronis type orbits, confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Close examination of the model profiles reveals that they are slightly broader than the observed profiles, indicating a distribution of asteroidal material with heliocentric distance r of the form $1/r^\gamma$ with $\gamma < 1$, rather than $\gamma = 1$ expected for a simple P-R drag distribution.

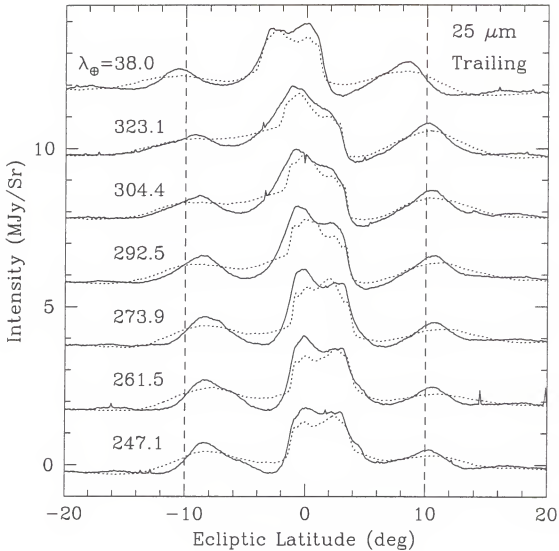


Figure 5-25: The observed 25 micron IRAS dust band profiles (solid lines) in the trailing direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits allowed to spiral into the inner solar system via P-R drag. Because of a parallax effect the latitudes of peak intensity move away from the ecliptic, and to preserve the model peak latitudes at the observed values, the dispersion in the orbital inclinations of the Eos material is increased to 3.5° . Themis and Koronis type orbits, confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Close examination of the model profiles reveals that they are slightly broader than the observed profiles, indicating a distribution of asteroidal material with heliocentric distance r of the form $1/r^\gamma$ with $\gamma < 1$, rather than $\gamma = 1$ expected for a simple P-R drag distribution.

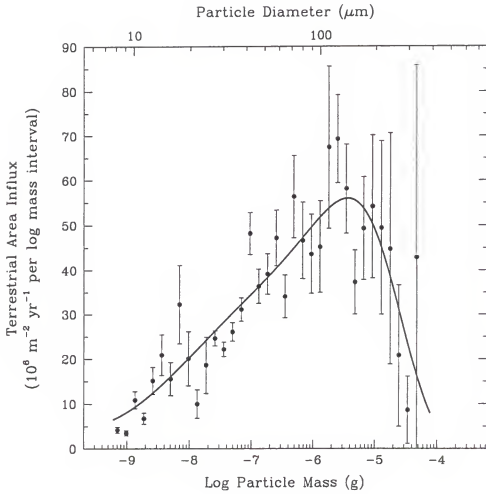


Figure 5-26: The terrestrial influx of zodiacal dust particles, as measured from the cratering record on the LDEF satellite. The slope of area against particle mass indicates a value for q , the size-frequency distribution index, of approximately 1.1.

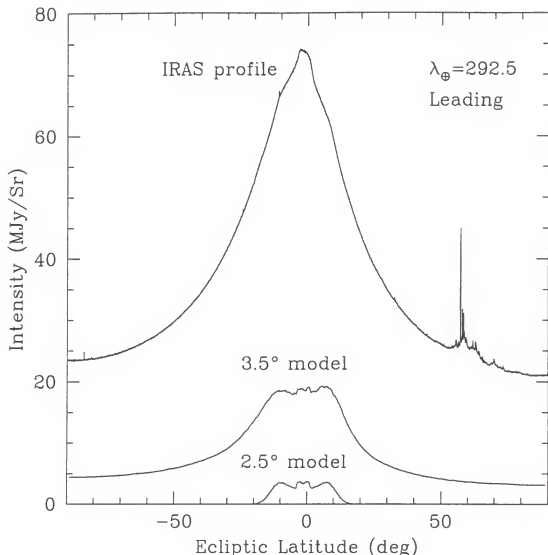


Figure 5-27: The contribution of asteroidal material to the zodiacal cloud. The figure shows the level of emission produced from two unfiltered dust band profiles, one taken from the 2.5° model, the other from the 3.5° model. The corresponding IRAS profile is also shown for comparison. The peak dust band emission from the 2.5° model is approximately 5% of the peak zodiacal background emission. However, the emission from the 3.5° model is significantly higher with a peak intensity approximately 25% that of the zodiacal background. This is because the material populating the inner solar system is warmer and closer to Earth. If the ratio of dust production by asteroid families to dust production by all asteroids is approximately 1:3, then this would imply that based on the dust band models presented, up to 75% of the zodiacal cloud, in terms of the material which gives rise to the thermal emission produced in the 25 micron waveband, may be asteroidal.

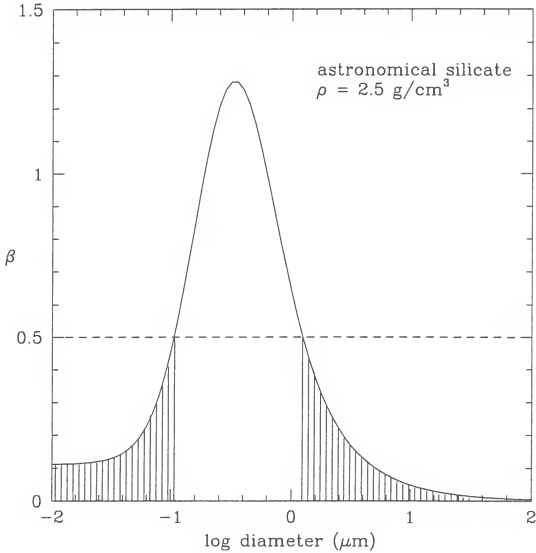


Figure 5-28: The variation of β (the ratio of radiation pressure to the gravitational force) with particle size for astronomical silicate particles having a density of 2.5 g/cm^3 . Particles are assumed to be blown out of the Solar System if their β is greater than 0.5. Notice that there are two size regimes in which particles 'survive' radiation pressure: diameters greater than approximately 1 micron and less than approximately 0.1 micron.

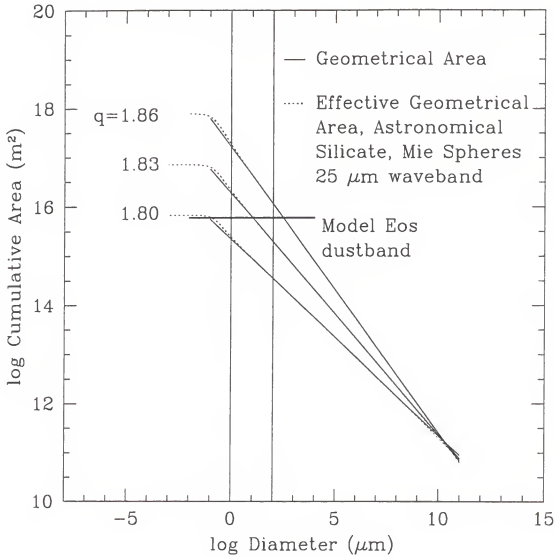


Figure 5-29: The sensitivity in cumulative effective area of particle distributions as seen in the 25 micron waveband, differing in size frequency index q by only 0.06. Notice that particles less than approximately 0.1 micron in diameter do not contribute to the flux seen in this wave band.

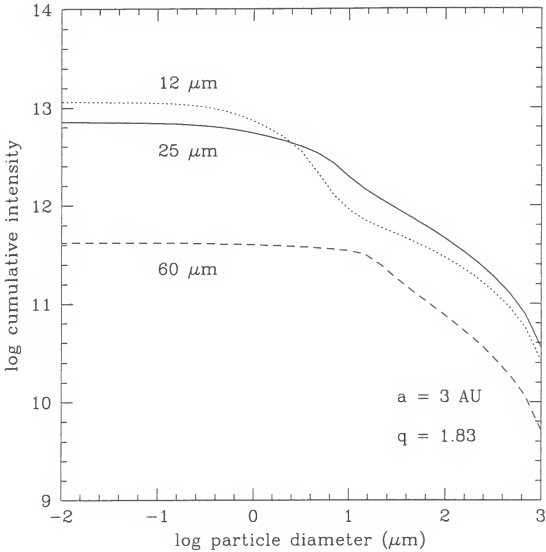


Figure 5-30: The flux contributions to the 12, 25 and 60 micron wave bands from astronomical silicate dust particles at 3 AU with a size-frequency index q of 1.83. The contributions to the 12 and 25 micron wave bands level off at a particle diameter of approximately 0.1 micron. The 60 micron wave band has negligible contribution from particles smaller than approximately 10 microns.

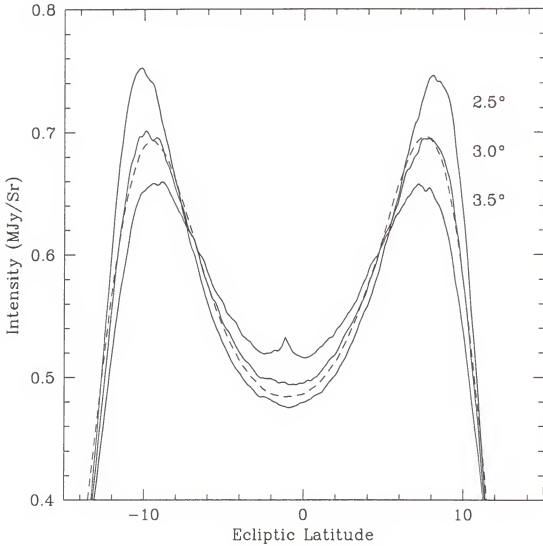


Figure 5-31: Raw Eos dust band profiles, produced by material confined to the asteroid belt (semi-major axis > 2.0 AU) with Lorentz dispersions of 2.5° , 3.0° and 3.5° at the edge of the asteroid belt. The 3.0° model matches reasonably well the original Eos model (dotted, intrinsic dispersion 2.5°).

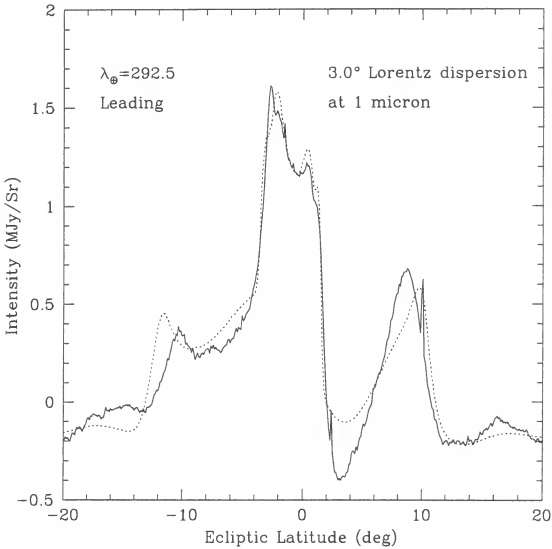


Figure 5-32: The result of combining 16 Eos dust band profiles representative of particle sizes between 1 and 100 microns according to a size frequency distribution with index $q=1.83$, and filtering, in order to compare the result with the IRAS observations. Each model has Lorentz-type dispersion in the orbital inclinations appropriate to its particle size. The 3.0° Lorentz dispersion was assigned to the 1 micron particles, the smallest particle size in the distribution. Although the total surface area is concentrated in the 1 micron particles (approximately 80%), the remainder is assigned to larger particles by the size-frequency distribution. Because of the strong inverse dependence of the Lorentz dispersion with particle size, the large material has little dispersion, and shows up as a peaky structure, similar to that shown in Figure 5-14.

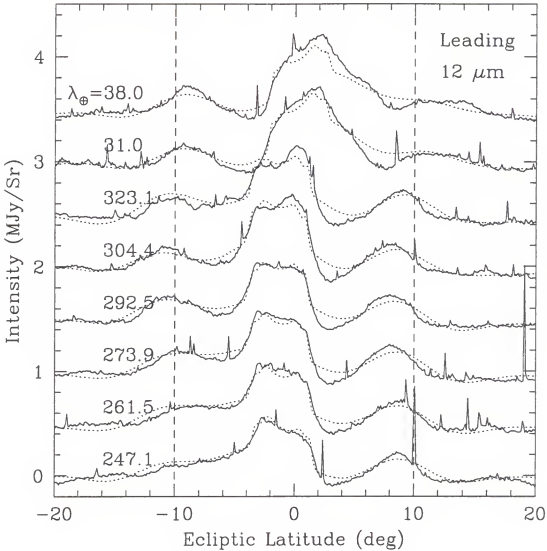


Figure 5-33: The observed 12 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. Particle sizes in the model range between 1 and 100 microns and are weighted according to a size frequency distribution with index $q=1.83$. The surface area of material associated with each family is given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Overall, the shapes of the models are consistent with the observations.

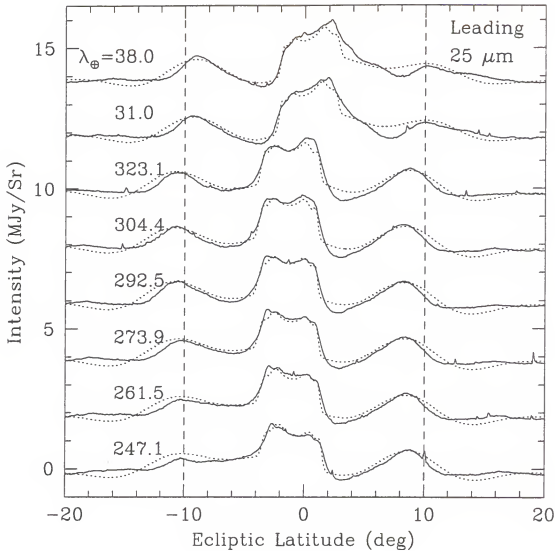


Figure 5-34: The observed 25 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. Particle sizes in the model range between 1 and 100 microns and are weighted according to a size frequency distribution with index $q=1.83$. The surface area of material associated with each family is three times that given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Overall, the shapes of the models are consistent with the observations.

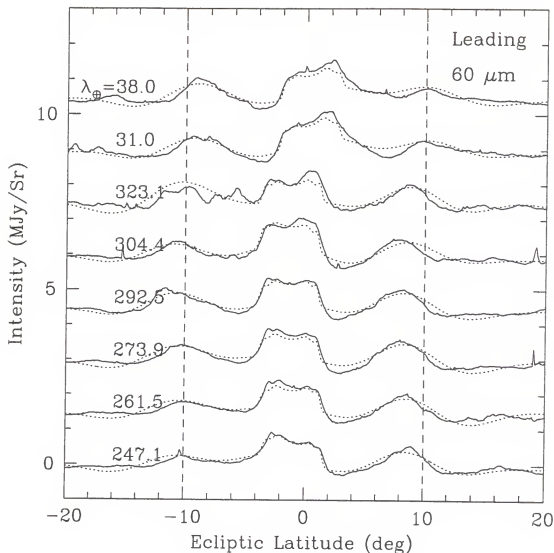


Figure 5-35: The observed 60 micron IRAS dust band profiles (solid lines) in the leading direction are compared to model profiles (dotted lines) obtained from a dust band model composed of Eos family type orbits confined to the asteroid belt (semi-major axis $> 2.0\text{AU}$) with a dispersion in proper inclination of 2.5° . Themis and Koronis type orbits, also confined to the asteroid belt with dispersions in proper inclination equal to the corresponding family member asteroids constitute the central band. Particle sizes in the model range between 1 and 100 microns and are weighted according to a size frequency distribution with index $q=1.83$. The surface area of material associated with each family is nine times that given in Table 5-1. Dashed vertical lines are placed at $\pm 10^\circ$ for reference. Overall, the shapes of the models are consistent with the observations.

CHAPTER 6 CONCLUSIONS

An understanding of the structure and evolution of our zodiacal cloud is of critical importance. Apart from the necessity to comprehend the rich detail in our local environment which in turn will give clues as to the origin of our solar system, knowledge of the structure of our own cloud can be used in the interpretation of the structure of zodiacal clouds around other stars, and possibly be used to indirectly detect the presence of planets. The debate over the cometary or asteroidal nature of our zodiacal cloud is far from decided, but the existence of the dust bands provides the best chance of estimating the asteroidal contribution. Dust band material has to be asteroidal. Comets cannot produce well defined dust bands. Accurate modeling of known asteroidal material should lead to a good estimate for the nature of the zodiacal cloud: predominantly asteroidal, cometary or a mixture of both.

The following conclusions can be made from the modeling of the dust bands discussed in the previous chapter:

1. The dust bands observed by IRAS can be well reproduced by material originating from the three main Hirayama asteroid families: Eos, Themis and Koronis.

2. The dust bands are best reproduced by a model which confines the material to the asteroid belt (semi-major axis $> 2.0\text{AU}$). In this case the dispersion of the orbital inclinations of the Eos material must be increased to 2.5° , almost nine times the dispersion in the Eos family members.
3. If the Eos material is allowed to populate the inner solar system, the dispersion in orbital inclinations must be increased to 3.5° to retain the peak latitudes of the bands at the observed values. This model produces 10° band profiles broader than those observed, implying that if the asteroidal material follows a distribution of the form $1/r^\gamma$ then $\gamma < 1$ rather than $\gamma = 1$ expected for a P-R drag distribution. This in turn implies a loss of material from the system due to interparticle collisions as it spirals in towards the Sun.
4. The 2.5° and 3.5° models for the Eos dust band material suggest contributions to the peak flux as observed by IRAS from the dust bands of approximately 5% and 25% respectively. If the family asteroid dust production rate to non-family dust production rate is approximately 1:3, then this implies that up to 75% of the zodiacal cloud is asteroidal.
5. Simple modeling of the effect of the Lorentz force on inclinations seems to suggest that it is not the source of the dispersion in the Eos particle orbits.
6. Inclusion of a size-frequency distribution in the modeling of the 2.5° best fit model indicates that there is a deficit of large particles in the modeling, consistent with a size-distribution varying with heliocentric distance with

larger particles increasing in number in the inner Solar System, as indicated by LDEF cratering records.

These conclusions pose questions of their own. For example, why is the dispersion imposed on the Themis and Koronis type material to model the central band simply the dispersion associated with the corresponding asteroid family members, while the Eos material requires an additional dispersion to match both the shape and latitude of the observed band? Perhaps this is more evidence that the material associated with the Eos family itself is more highly dispersed than the dispersion of the largest family members indicates. This problem may however be instructive in itself in providing insights to ongoing physical processes in the belt - perhaps the low dispersion central band models point to more recent collisions within the family, and serves to illustrate the power of the dynamical treatment over the empirical rotationally symmetric model.

Future Work

The contrasting pictures of a source in collisional equilibrium and the LDEF cratering record indicating a surfeit of large particles near the Earth highlight the difficulty of producing models for the Solar System dust bands which 'explain all'. The evidence from LDEF and the Earth's resonant ring is clear: asteroidal material reaches the inner Solar System, although presumably processed in some way, most likely by collisions. The models produced to

populate the inner Solar System suggest that in addition to this the distribution of material with heliocentric distance will vary not as $1/r$ as expected by P-R drag but will be more concentrated in the asteroid belt. This dissertation includes the first dust band models which include a size-frequency distribution of material, an important step forward from the single size models which themselves were far in advance of empirical models of the dust bands available elsewhere in the literature. Future models will need to address the simultaneous adjustment of both the size-frequency distribution of the material and the variation in number density of the material with heliocentric distance in order to achieve a more accurate model of the distribution of dust band material. The consideration of different particle sizes in the cloud as a whole has important consequences, particularly as the particles move into the inner solar system via P-R drag. Indeed, the inclusion of a range of particle sizes produces an unavoidable, natural dispersion as particles pass through an inclination-type secular resonance at the inner edge of the asteroid belt (Dermott et al. 1990). Dispersion in proper inclination also occurs on passage through the Kirkwood gaps.

The IRAS view of the dust bands is rather limited in that most data was taken around solar elongation 90° . The sky maps produced by COBE between 64° and 124° elongation angle allow a view of the inner Solar System, and further information will be gathered from missions such as ISO and SIRTf. These data will help to reveal the three-dimensional structure of the dust bands, will show

the extent to which Themis, Koronis and Eos material may be allowed to populate the inner Solar System, and will pin down the asteroidal contribution to the cloud. An huge step will then have been made towards answering the old question: 'Zodiacal cloud, cometary or asteroidal?'

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BIOGRAPHICAL SKETCH

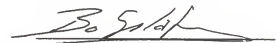
Keith Grogan was born in 1970, raised in Liverpool, England and survived a Roman Catholic school education relatively unscathed. While gazing at the southern sky from the back of a pick-up truck in Zambia in December of 1987, he made the fateful decision to read astronomy at university rather than medicine. Shortly afterwards he went up to the University of St. Andrews in Scotland, where he earned his undergraduate degree in Astronomy and Astrophysics in the summer of 1992. He did not, however, play a single round of golf during his four year stay. From there he proceeded to the University of Florida where he has shown the impudence of attempting to obtain a doctorate.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Stanley F. Dermott, Chair
Professor of Astronomy

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Bo A. S. Gustafson
Associate Professor of Astronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Haywood C. Smith
Associate Professor of Astronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Yu-lin Xu
Assistant Scientist

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



Neil S. Sullivan
Professor of Physics

This dissertation was submitted to the Graduate Faculty of the Department of Astronomy in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as a partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1997

Dean, Graduate School